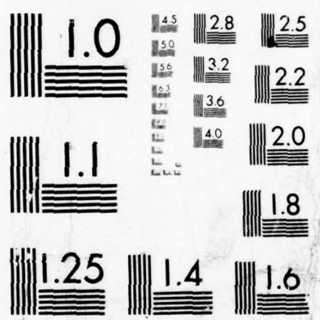
AD-A069 691 UNITED TECHNOLOGIES CORP STRATFORD CT SIKORSKY AIRCR--ETC F/G 1/3
HELICOPTER DRIVE SYSTEM R AND M DESIGN GUIDE.(U)
APR 79 K R CORMIER, B TRUSTEE DAAJ02-76-C-0047
UNCLASSIFIED SER-510012 USARTL-TR-78-51 NL

1 OF 2
AD
A069691


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3

USARTL-TR-78-51

LEVEL II

12

FINAL REPORT, HELICOPTER DRIVE SYSTEM R&M DESIGN GUIDE

K. R. Cormier, B. Trustee
SIKORSKY AIRCRAFT
Division of United Technologies Corp.
Stratford, Conn. 06602

April 1979

Final Report

Approved for public release; distribution unlimited.

Prepared for

APPLIED TECHNOLOGY LABORATORY
U. S. ARMY RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM)
Fort Eustis, Va. 23604

APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

Drive system components are among the largest contributors to Army helicopter reliability and maintainability problems. Past studies have focused on identifying the magnitude and nature of the problems. Other efforts have investigated the potential R&M benefits of specific design concepts. Extensive work has been performed in establishing the feasibility of "on-condition" maintenance. An extensive effort continues to address diagnostics. Much of the documentation of these endeavors has been written expressly for the R&M engineer--in a technical jargon incomprehensible to many designers.

The objective of this contract was to "translate" the aforementioned endeavors putting R&M into proper perspective, thereby making design engineers more conscious of the R&M aspects of the drive systems they design. The results are published in two reports: TR 78-50, Helicopter Drive System R&M Design Guide, and TR 78-51, a final report documenting the program.

The approach was to analyze failure modes experienced, contrasting them to current practices to determine design, development, and overhaul deficiencies. Analytical methods for estimating "off-the-board" reliability were reviewed. Testing methods, specifically accelerated testing versus overload testing, and reliability growth were addressed. On-condition maintenance and diagnostics were also addressed. Positions in two of these areas follow.

Reliability estimation needs more work to achieve parity with strength and weight analyses. Hazard functions could not be correlated with such design parameters as load or induced stress, precluding the assignment of "hard" numbers to reliability estimation. Probabilistic design is the best way to predict service life. It has the potential for optimum utilization of weight, and is the only means for setting realistic bounds on reliability problems involving costs, warranties, and producer's risk. The R&D necessary to bring probabilistic design "on stream" is encouraged.

Regarding diagnostics, fuzz burn-off chip detectors coupled with superfine filters are seen as the simplest, most cost-effective diagnostic system for modern helicopter drive systems. Fine filtration has the potential for rendering spectrometric oil analysis (SOAP) and particle count techniques obsolete. The Automatic, Inspection, Diagnostics, and Prognosis System (AIDAPS) requires very sophisticated instrumentation. Without a breakthrough in understanding the sympton-failure relationship, development of a practical, cost-effective AIDAPS system appears remote.

This program was conducted under the technical cognizance of Joseph H. McGarvey, Aeronautical Systems Division.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

19 REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 18 USARTL TR-78-51	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* 6 ~~FINAL REPORT~~ HELICOPTER DRIVE SYSTEM R&M DESIGN GUIDE.		5. TYPE OF REPORT & PERIOD COVERED 9 Final Report. Fand I
		6. PERFORMING ORG. REPORT NUMBER 14 SER-510012
7. AUTHOR(s) 10 K. R. Cormier B. Trustee		8. CONTRACT OR GRANT NUMBER(s) 15 DAAJ02-76-C-0047
9. PERFORMING ORGANIZATION NAME AND ADDRESS 3 Sikorsky Aircraft Div ~~Division of~~ United Technologies Corp. 2 Stratford, Connecticut 06602		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 16 [redacted] 1L262209AH76 17 00 199 EK
11. CONTROLLING OFFICE NAME AND ADDRESS Applied Technology Laboratory, U.S. Army Research & Technology Laboratories (AVRADCOM) Fort Eustis, Virginia 23604		12. REPORT DATE 11 Apr[redacted]79
		13. NUMBER OF PAGES ~~136~~ 12 137p.
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Gears	Helicopters
Bearings	Reliability
Transmission	Maintainability

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report covers the investigations conducted during the Helicopter Drive System R&M Design Guide program. The report discusses the present state of transmission reliability and how reliability and maintainability are dealt with during the design and development of a helicopter drive system. Other topics discussed include the effect of quality control on drive system reliability, drive system maintainability problems, diagnostics, and the likely effect of advanced design concepts on the reliability and

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-014-6601

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

323800

79 06 11 017

20. Abstract (Cont'd)

maintainability of future drive systems. Two different types of reliability prediction techniques, hazard function analysis and probabilistic design, are discussed, and the strengths and weaknesses of each are outlined. Test planning and maintainability analysis are included as separate appendices.

PREFACE

This report was produced as part of the Drive System R&M Design Guide Program under Contract DAAJ02-76-C-0047 for the Applied Technology Laboratory, U. S. Army Research and Technology Laboratories (AVRADCOM), of Fort Eustis, Virginia. Technical direction for this program was provided by Mr. J. McGarvey of the Applied Technology Laboratory. Mr. C. Keller served as Program Task Manager at Sikorsky.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

Figure		Page

LIST OF TABLES

INTRODUCTION

In recent years there has been increasing emphasis on improving the reliability and maintainability of helicopter subsystems. This increased emphasis has resulted from the realization that improved reliability and maintainability can substantially increase the helicopter's overall cost effectiveness. In view of this, many R&D programs have been directed at enhancing the R&M characteristics of helicopter drive systems. Unfortunately, much of the literature produced in these efforts has been written from the standpoint of the R&M engineer. As such, the literature is written largely in the technical jargon of reliability engineering, which is incomprehensible to most design engineers. A second and perhaps more serious shortcoming with many of these reports is that they have addressed the problem of transmission reliability and maintainability as an isolated one without considering many of the constraints and limitations involved in the design of a helicopter drive system. This has resulted in a considerable misrepresentation of the difficulty in accurately assessing or substantially improving the reliability and maintainability of a drive system during the design stage.

The relative importance of high transmission reliability and maintainability can best be evaluated by examining the impact of reliability and maintainability factors on such parameters as aircraft cost effectiveness, aircraft mission effectiveness, and aircraft life-cycle cost. Such parametric analyses can provide a common basis for judging the relative value of such diverse factors as reliability and weight or measuring the effect of increases or decreases in these factors.

To illustrate the relative importance of reliability and maintainability, it is useful to examine a life-cycle cost breakdown of a typical military helicopter, as shown in Figure 1. The percentages shown in this chart are, of course, approximate and will vary depending on the physical size, purpose, and fleet size of the aircraft. In general, the larger the size of the aircraft, the lower the proportion of operating costs, and the larger the fleet size, the higher the proportion of operating costs. Regardless of any of these parameters, however, maintenance remains by far the most significant design-sensitive item in the life-cycle cost of an aircraft.

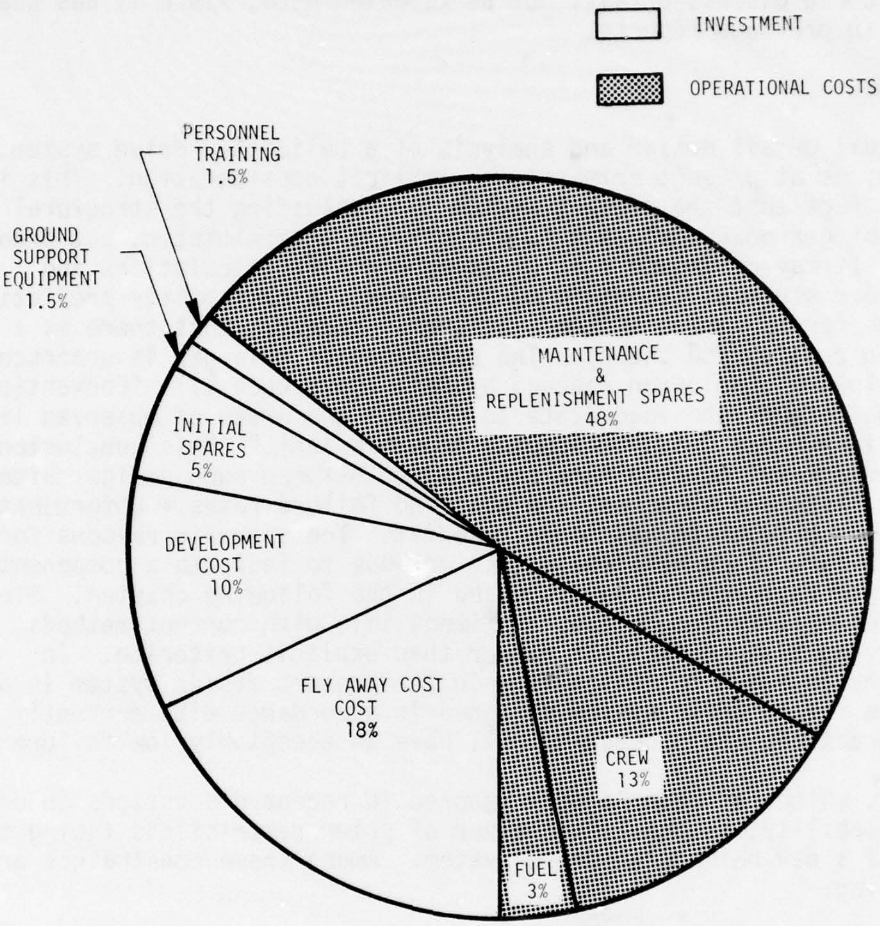


Figure 1. Typical Life-Cycle Cost Breakdown For Military Helicopter.

RELIABILITY GROWTH IN A TYPICAL HELICOPTER TRANSMISSION

The evolution of a helicopter drive system occurs in basically three phases: design, test and development, and production. This chapter will discuss how the problem of reliability is addressed during each of these three stages. The topic of classic reliability growth with its attendant "bathtub" curve discussion will not be repeated here, since it has been presented in previous reports.

DESIGN STAGE

In the actual detail design and analysis of a helicopter drive system, reliability is at present primarily an implicit consideration. This is due to the fact that the present system for evaluating the structural integrity of gearbox components is essentially deterministic, not probabilistic. It may be argued that by using B_{10} life calculations and relating gear stresses to published S/N curves, a reliability prediction may be made for the drive system. It seems, however, that there is a wide gap between reality and theory. The existence of this gap is underscored by the following conclusion reached by Bell (Reference 1): "Conventional engineering methods are inadequate to predict the order of observed life or the failure modes (in a helicopter transmission)." This conclusion was based on an attempt to find some correlation between such design criteria as bearing lives and stresses, and observed failure rates. Unfortunately, little or no correlation was found to exist. The specific reasons for the apparent failure of current analytical methods to indicate a component's propensity to failure will be discussed in the following chapter. Since accurate reliability predictions are impossible with current methods, reliability must be an implicit rather than explicit criterion. In essence, the approach to reliability in the present design system is understood to be that a drive system designed in accordance with currently accepted practices and procedures will have an acceptably low failure rate.

One factor, which has been largely ignored in recent discussions on drive system reliability, is the large number of prior restrictions facing the designer of a new helicopter drive system. Among these constraints are the following:

- Power
- Envelope
- Reduction Ratio
- Input/Output Locations
- Rotor/Control Loads
- Accessory Requirements
- Weight
- Reliability/Maintainability

---

[1] Bowen, C. W., et al., MODE OF FAILURE INVESTIGATIONS OF HELICOPTER TRANSMISSIONS, Bell Helicopter Company; USAAVLABS Technical Report 70-66, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1971, AD 881610.

- Survivability/Vulnerability
- Producibility
- Cost

These criteria, which must be met if the aircraft is to meet its performance requirement, drastically limit the options open to the gearbox designer. Furthermore, with the existing design system, such factors as weight will usually take precedence over such factors as reliability in design tradeoffs. Unlike reliability, weight is easily determined with great accuracy. Hence, in any design tradeoff, the design of the least weight has a definite quantifiable payoff. A heavier, albeit more reliable design, has a definite quantifiable penalty. The magnitude of any improvement in reliability, given the state of current engineering methods, would be impossible to determine with certainty. In a weight/maintainability tradeoff, the difficulty in proving that the more maintainable design is the "better" choice is even greater.

One approach to predicting reliability, which has recently been adopted, is hazard function analysis. A hazard function expresses, for a particular failure mode of a component, its failure rate as a function of time. By developing hazard functions for all possible failure modes of all gearbox components, it is possible to combine them for an overall gearbox hazard function that can be used to describe the reliability of a gearbox as a function of time.

One purpose of this program was to develop general hazard functions for each failure mode of each generic component so that gearbox hazard functions could be calculated during the design stage. This would enable the design engineer to evaluate the reliability of his design and to determine to some extent if the design would meet the required MTBF. It would also allow him to focus his attention on areas where improvement would have the greatest impact in improving the gearbox MTBR. It was also hoped that some relationship could be developed between hazard function parameters and design parameters such as stress, which would allow the design engineer to make quantitative design tradeoffs based on reliability.

These goals were only partially achieved. First, the overwhelming majority of the data, which was to be used for generating the general hazard functions, was not at all suited to this purpose. Hence, it was decided to use only CH-54 and H-53 data for generating the hazard functions. Second, it was found that no definite relationship could be established between hazard function parameters and design parameters such as stress. There are two reasons for this. First, the data on which the hazard functions are based are not sufficient in quantity or quality to be sure that they provide an accurate picture of the reliability characteristics of the gearbox components. Second, present engineering analytical techniques are, in general, not accurate enough to provide a true indication of a parts tendency to failure. The reasons for this will be expanded upon in the following chapter.

The fact that hazard function parameters could not be related to design parameters does not, however, negate the usefulness of this technique to design engineers. The general hazard functions that will be included in the design guide can be used in two ways by design engineers. First, if a hazard function analysis is performed on a proposed design early in the design stage, the upper and lower bounds of the MTBF for the design can be determined. From this an evaluation of the adequacy of the design from a reliability standpoint can be made. If it is decided that the hazard function analysis shows the MTBF to be lower than required, the hazard function analysis can be examined to determine where redesign will have the greatest impact in improving the design MTBF.

Before completing this discussion of the design of a helicopter transmission, it is necessary to correct the impression that power, mission profile, and gross weight directly affect the reliability of transmission components. Transmission components are designed on the basis of stress, bearing lives, and other similar parameters. Such quantities as power are used to determine these parameters. However, the design stress levels do not change with either the power, gross weight, or mission profile of an aircraft.

Transmission components of a lightweight/low power aircraft will be designed to exactly the same stress levels as a high gross weight/high power aircraft. The reason that high power aircraft exhibit lower MTBR's than low power aircraft has nothing to do with the design criteria. Higher power aircraft generally require more gear meshes because of multiple engine inputs. This requires a more complicated transmission with a higher parts count and hence, lower reliability. The larger aircraft also generally have more accessories, which further increases the parts count. Hence, those curves that show trends between MTBR and power are misleading in that the cause for the difference in MTBR is misrepresented.

On-condition maintenance (i.e., operation without a specific TBO) is another concept that has been the subject of much discussion recently. Several studies have shown conclusively that on-condition maintenance is a cost-effective practice and should be instituted wherever practical. The cost advantages of an on-condition maintenance policy are well documented and will not be repeated here. If it can be shown that there is essentially no increase with time in the incidence of failure modes that affect the safety of flight, an on-condition maintenance can be instituted. There are relatively few failure modes in helicopter drive systems that could be said to affect flight safety. Chief among these is probably gear tooth breakage. The advent of vacuum-melt gear steels, however, has practically eliminated gear tooth breakage as a failure mode. The few gear tooth failures that are experienced can usually be traced to a quality control problem. Hence, rather than there being any specific design practices that permit on-condition maintenance, advances in material technology appear to be mostly responsible.

TEST AND DEVELOPMENT STAGE

There are three basic types of tests that are performed during the development of a helicopter drive system: individual component tests, subsystem bench tests, and integrated system tests. The first type of test is, with one exception, usually not conducted during the development of a helicopter drive system. Individual component tests are generally reserved for research and development efforts unless a relatively new concept has been included in the drive system design. The one component that is tested separately is the main rotor shaft. The main rotor shaft is usually, except for bearings, the only life-limited transmission component. As such, demonstration of the fatigue life by test is required by both military and civilian regulations.

Subsystem bench tests are from the transmission designer's viewpoint perhaps the most important tests performed on the transmission. Bench tests encompass a wide range of tests including no-load lubrication tests, gear pattern development tests, acceptance tests, endurance tests, and overstress tests. For the purpose of this discussion, we will confine ourselves to the latter two types of tests, since these are the only ones which bear directly on demonstrating reliability. Endurance tests are generally conducted over a power spectrum somewhat representative of the power spectrum that is anticipated for the aircraft. Overstress tests, as the name implies, are conducted at powers exceeding those anticipated in normal aircraft operation. Accelerated testing of this type has the advantage of more rapidly uncovering certain types of design deficiencies than normal endurance testing. Overstress testing, however, should not average much over 110 percent of the design power. Extended running at powers greater than this can lead to failure modes not characteristic of the gearbox operating under normal powers. Excessive power will cause the housing and gearshafts to deflect excessively. This in turn can lead to improper loading of gear teeth, which can result in premature gear failure or excessive shaft slope, which can result in premature bearing failure.

There are two basic types of integrated system tests, aircraft tiedown tests, and flight tests. Aircraft tiedown tests are essentially "flight" tests with the aircraft tied to the ground. This type of test is very valuable, since flight conditions can be simulated very closely without incurring the risk involved in actual flight tests. Both types of test are important, since they allow the performance of the transmission to be monitored as it interfaces with the other aircraft systems. Of particular interest in these tests are the magnitude of the loads that other systems such as controls and rotors impose on transmission components. More than once transmission components have been redesigned because flight and tiedown tests showed these loads to be much higher than predicted.

Test Program

There have been a number of studies whose purpose was to develop methods for formulating test programs that would assure that required drive system reliability levels would be achieved when the aircraft was fully developed.

The one factor all of these methods have in common is that they make unwarranted assumptions that render them invalid. First, field reliability levels cannot be determined in a bench test regardless of the length of the test. The bench test environment is not sufficiently close to that of the operational environment to assume that the reliability observed in the test stand will be the reliability observed in field operation. Second, it would be cost prohibitive to test a statistically meaningful number of gearbox samples. Yet many of these methods suggest that reliability levels can be demonstrated with one or two samples. It is time to recognize the fact that transmission reliability levels cannot be realistically demonstrated in test programs.

For helicopter transmission systems, a test program such as that conducted during the UTTAS program appears to be the most practical approach. The UTTAS transmission development test program consisted basically of three phases of bench testing in addition to the aircraft tiedown and flight tests. The three phases of bench testing were preliminary qualification, overstress, and qualification tests. The purpose of the preliminary qualification test was essentially to verify the integrity of the gearbox design. Although this test consisted of 200 hours of running at 100 percent design power, there is no reason that the test could not be longer or shorter depending on design complexity. The second bench test performed during UTTAS development was the overstress test. The primary purpose of the overstress test, which also consisted of 200 hours of testing, was to identify problems of a fatigue nature, which at normal loads would not have become evident during the relatively short test durations. This test accomplished its purpose very well during Sikorsky's UTTAS development program,since it did uncover one problem of fatigue nature that could have become very troublesome later, had it not been detected during this test. The test spectrum of the UTTAS overstress test is shown in Table 1.

TABLE 1. YU-60A (UTTAS) 200-HOUR OVERSTRESS DEVELOPMENT TEST SPECTRUM

% Power	% Time	% Power	% Time
134	1.5	93	4.6
129	7.0	89	1.0
123	6.0	87	1.5
121	6.3	140*	.45
112	7.1	140*	.45
111	30.3	68	2.6
103	26.7	112*	.75
101	3.0	112*	.75

*Single engine only

After the overstress test the transmission was subjected to the qualification test, which, like the preliminary qualification, was run at a spectrum approximating that expected in normal operation. The effectiveness of this test program is testified to by the fact that during subsequent prototype tests the YUH-60A transmission was virtually trouble-free with no discrepancies even remotely approaching a major failure.

PRODUCTION

With an aircraft into production and field operational, the importance of attention to reliability and maintainability during design becomes very evident. Serious reliability and maintainability problems may take years to correct during this stage if they are corrected at all. There are several reasons for this. First, the designer can no longer directly monitor the performance of the system. He is dependent on the operator and product support personnel for information on design deficiencies uncovered during operation. Second, even if he is informed of problems in the field, authorizaton to take corrective action can be slow in coming. Moreover, incorporation of design improvements can be very expensive and can take years to complete. In short, it is infinitely preferable to deal with reliability and maintainability during the design or test stage rather than during the production stage.

Once an aircraft enters the production stage, the gearbox design engineer should continue to monitor the performance of the drive system as closely as possible. This should not be done by simply reading disassembly reports or by reading memos from product support. Rather, the design engineer should periodically spend some time at depot observing firsthand the teardown of gearboxes returned for overhaul. This will serve two purposes. First, the gearbox designer will be able to more accurately assess the cause of gearbox problems. This will permit quicker incorporation of design changes if deemed necessary. Second, the experience the designer gains by inspecting actual field failures will prove valuable in the design of future systems.

TRANSMISSION COMPONENT RELIABILITY

The fact that transmission components fail when they are not supposed to is why programs such as this are necessary. There are a number of reasons for premature failure, many beyond the control of the transmission designers. These include defective components, assembly errors, ballistic damage, and component overload. There are many other failures, however, which occur because of inadequacies in the design analysis that was used. This chapter will concern itself only with primary failure modes, which are commonly known as dynamic component removal failures. The discussions for each component will proceed in the following manner. First, a list of possible failure modes is compiled for each gearbox component. These failure modes are then examined to determine their possible causes. For each cause of a failure mode, a determination is made if an analytical technique exists that accounts for the cause. An evaluation is then made of its effectiveness. If an analytical technique does not exist, possible ways of dealing with the cause of the failure mode are discussed. The procedure is illustrated in Figure 2.

BEARINGS

Bearing failure has historically been the most common reason for premature removal of helicopter gearboxes. This is not surprising, given the number of bearings included in helicopter transmissions and the severe conditions under which they must operate. Table 2 summarizes the most frequent bearing failure modes, which result in premature gearbox removal. Spalling, shown in Figure 3, is by far the most common failure mode.

TABLE 2. BEARING DYNAMIC COMPONENT REMOVAL FAILURE MODES

Failure Mode	Failure Mechanism	Cause	Accounted for Analytically
Spalling	Subsurface Fatigue	Inclusions	Yes
	Surface Fatigue	Indentations	No
	Surface Fatigue	Corrosion Pit	No
Smearing	Heat Imbalance	Lack of Lubrication	Yes
Seizure	Heat Imbalance	Lack of Lubrication	Yes
Cage Fracture	Fatigue	Understrength	No

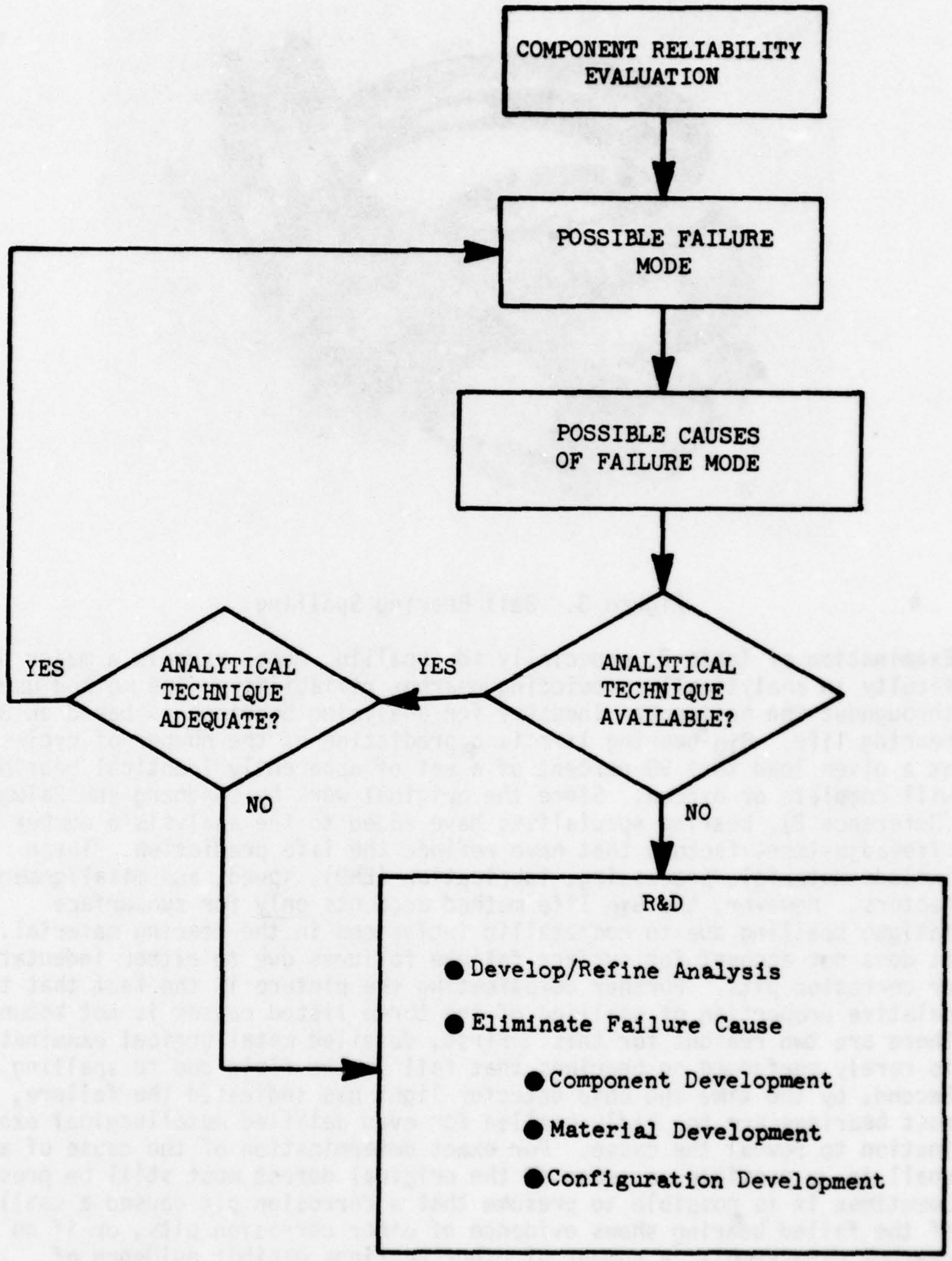


Figure 2. Dynamic Component Reliability Evaluation.

Figure 3. Ball Bearing Spalling.

Examination of Table 2, especially the spalling mode, reveals a major difficulty in analytically predicting gearbox reliability. The method used throughout the helicopter industry for analyzing bearings is based on B_{10} bearing life. B_{10} bearing life is a prediction of the number of cycles at a given load that 90 percent of a set of apparently identical bearings will complete or exceed. Since the original work by Lundberg and Palmgren (Reference 2), bearing specialists have added to the analysis a number of life-adjustment factors that have refined the life prediction. These include material, processing, lubrication (EHD), speed, and misalignment factors. However, the B_{10} life method accounts only for subsurface fatigue spalling due to nonmetallic inclusions in the bearing material. It does not account for surface fatigue failures due to either indentation or corrosion pits. Further complicating the picture is the fact that the relative proportion of spalling of the three listed causes is not known. There are two reasons for this. First, detailed metallurgical examination is rarely performed on bearings that fail in the field due to spalling. Second, by the time the chip detector light has indicated the failure, most bearings are too badly spalled for even detailed metallurgical examination to reveal the cause. For exact determination of the cause of a spall to be possible, a trace of the original defect must still be present. Sometimes it is possible to presume that a corrosion pit caused a spall, if the failed bearing shows evidence of other corrosion pits, or if on gearbox disassembly, a number of other bearings exhibit evidence of

---

2 Lundberg, G., and Palmgren, A., DYNAMIC CAPACITY OF ROLLING BEARINGS, Royal Swedish Academy of Engineering Sciences, Stockholm, 1947.

corrosion. With present inspection procedures, however, usually no effort is made to determine the cause of a spall. It is reported simply as a spalled bearing.

Corrosion of bearings occurs when the gearbox lubricant becomes contaminated with water. If water contamination due to faulty seals is ignored, condensation becomes the primary mechanism for this contamination. Condensation occurs because of the heating and cooling cycles of the gearbox, and depends to a large extent on climatic conditions. Obviously, gearboxes operating in rain forests will be much more susceptible to condensation contamination than gearboxes operating in a desert environment. Since the problem of gearbox contamination due to condensation has never been studied, little is known of its effect on bearing corrosion. It is not known, for example, at what rate condensed water accumulates in a gearbox, or if there is a maximum permissible contamination level below which corrosion is unlikely. Suffice to say, given its time-dependent nature and the paucity of knowledge about it, the problem of water contamination warrants further investigation.

Indentation-caused spalling is another failure mode that is difficult to predict accurately. On the rolling surfaces of bearings, indentation damage is inflicted whenever a solid foreign particle is trapped in the contact area between the rolling element and the race. This indentation, which may be caused by either hard or soft particles, can lead eventually to spalling, the foreign particles that cause indentation may be wear particles generated within the gearbox or dust from the environment. Properly designed seals can largely prevent dust from entering the gearbox, but wear particles present a problem. As with water contamination, little is known at what rate these particles accumulate within the lubricant. It is obvious, however, that the level of contamination increases with time, and the higher the contamination level the more likely indentation and subsequent spalling of bearings will occur. A possible solution to this problem would be the incorporation of superfine filters (3 microns) such as those used on the latest turbine engines. Although early clogging problems with such superfine filters have been resolved, these filters do require a considerably larger space allocation than conventional gearbox filters.

Smearing and seizure are both caused by a heat imbalance within the bearing due to inadequate lubrication. Often such failures are secondary, resulting from a clogged jet or a failure in the lubrication system. The amount of lubricant required by a bearing is determined by calculating the bearing friction, converting that into heat units, and then determining the amount of lubricant required to remove the heat. The fact that there are relatively few primary bearing failures of this nature is testimony to the adequacy of this analysis. However, it must be pointed out that the analysis is adequate only for oil-lubricated bearings. It is not valid for grease-lubricated bearings, since the grease not only does not remove the heat, but acts as an insulator keeping the heat within the bearing. If grease-lubricated gearboxes become more widely accepted than they are now, further investigation of bearing heat balance will be required.

The final cause of bearing primary failure to be discussed here is cage fracture. While it is known that fatigue is the mechamism by which most cages fail, the loading of the cage is so complex that analysis of the cage for fatigue is generally not attempted. Fortunately, cage fracture is a relatively rare primary failure mode in bearings. Usually, if it occurs, it can be easily corrected by changing the cage to a stronger material.

There are two particular bearing applications that merit special attention because of the disproportionate number of primary failures that occur in them. The first of these applications is main rotor shaft support. The major problem with bearings in this application appears to be low EHD film thickness, which results from the relatively slow rotational speed of the main rotor shaft. Often when the recommended EHD factor is applied to the calculated B_{10} life of bearings in this application, the life theoretically approaches zero. Of course, in actual practice this does not prove to be the case, but it does indicate that the EHD factor generally applied to bearings ceases to be accurate in low-speed applications. To offset the inability of traditional bearing analysis to accurately predict the life of main rotor shaft bearings, it is recommended that the design approach to these bearings be somewhat conservative regarding both life and amount of lubricant supplied. The second bearing application, which is especially troublesome, is the planet pinion bearing. The problem with these bearings is the difficulty, because of their configuration, in providing adequate lubrication. This is true with both the thrust washer/roller and the spherical bearing designs.

GEARS

Gear failures, while not nearly as common as bearing failures, are important because a failure in a primary power train gear can jeopardize safety of flight. Table 3 lists the primary failure modes of gears.

TABLE 3. GEAR PRIMARY FAILURE MODES

Failure Mode	Failure Mechanism	Cause	Accountability by Analysis
Tooth Breakage	Bending Fatigue	High Stress	Yes
Pitting	Surface Fatigue	High Stress	Yes
Scoring	Asperital Contact	Lubrication Breakdown	Yes

Gear tooth bending failures, as illustrated by Figure 4, are extremely rare in current technology drive systems. This is due to the fact that with the vacuum-melt case carburizing steels used for today's aerospace gearing, compressive stress, not bending stress, is the limiting design

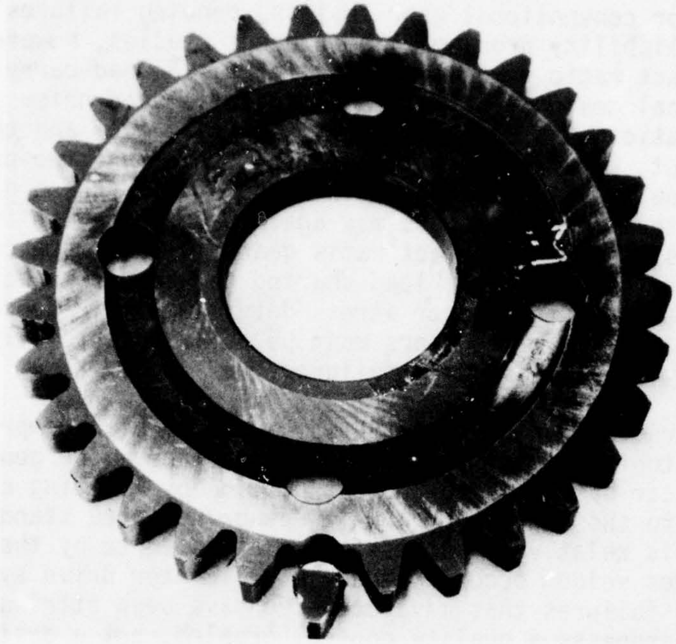


Figure 4. Gear Tooth Bending Failure.

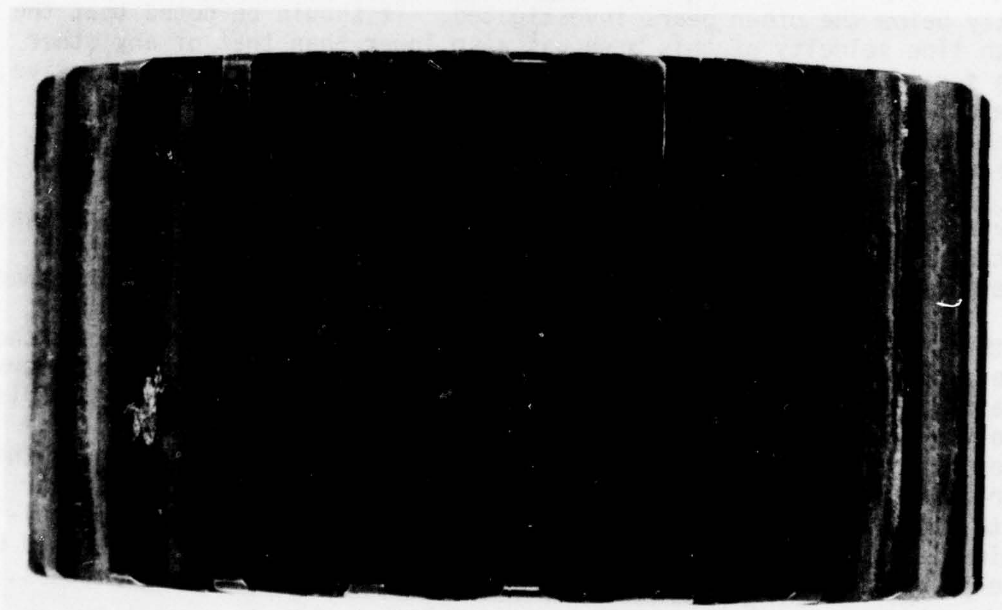


Figure 5. Gear Tooth Pitting Failure.

factor. Hence, the elimination of bending failures in gear teeth is more the result of material improvement than the result of improved analytical techniques. For conventional gear designs, bending failures should not be a potential reliability problem. Some recent studies, however, have shown that high contact ratio gears may offer increased load-carrying capability over conventional designs, as well as lead to reduced noise signatures. High contact ratio gears operate with alternately two- and three-tooth pairs in contact, compared with the alternate one- and two-pair contact with conventional gears. The potential problem with these gears arises from the fact that bending stress may again become the limiting design factor. Analysis of high contact ratio gears is much more complex than that of standard gears in that load sharing between tooth pairs must be accurately determined for proper stress determination. Hence, any design involving high contact ratio gears must be analyzed carefully to minimize the possibility of tooth bending failures.

Pitting of gears, shown in Figure 5, is caused by high compressive stresses that lead to fatigue of the gear tooth surface. The general practice in aerospace gear design is to prevent pitting by limiting compressive stress levels to those given by AGMA or other accepted standards. That this practice is relatively successful is attested to by the fact that pitting failures seldom occur in today's helicopter drive systems. Most of the pitting failures that have occurred have been attributed to insufficient case hardness, a quality control problem, not a design problem. A striking exception to this general trend was reported in Reference 1. A particular gear mesh, although designed with compressive stress well within the accepted limit, was subject to chronic pitting. Further investigation of the mesh in question showed an EHD film thickness significantly below the other gears investigated. It should be noted that the pitch line velocity of this mesh was also lower than that of any other mesh considered. While one case such as this is by no means conclusive, it might be advisable to check for adequate EHD film thickness as an added design criteria, especially for gears with relatively low pitch line velocities.

Scoring of gear teeth, illustrated in Figure 6, is produced by asperital contact between the surfaces of two meshing gear teeth and is caused essentially by lubrication breakdown. Scoring is not a fatigue phenomenon and it usually occurs quite rapidly. The generally accepted design criteria for scoring is flash temperature index, although some researchers have proposed that EHD film thickness be used instead. Scoring of gears is a relatively infrequent problem with current aerospace gearing and is rarely a cause for gearbox removal. In most instances scoring is discovered only at overhaul and is usually not serious enough to render the gear unserviceable. With grease lubrication, however, scoring of gear teeth could become a serious reliability problem. Before grease lubrication is used more extensively that it is today, some research should be done to better understand the mechanism of grease lubrication in gears.

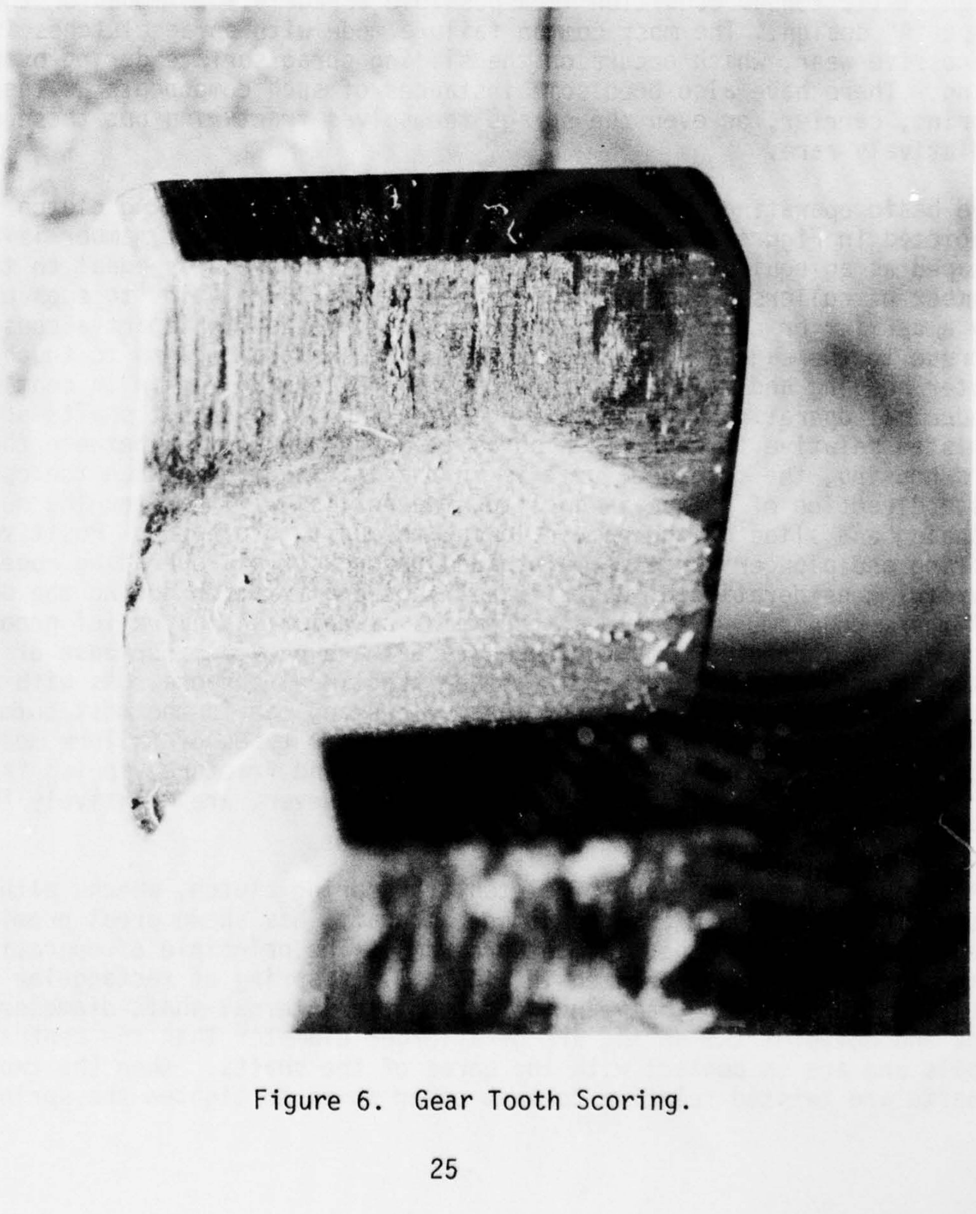


Figure 6. Gear Tooth Scoring.

CLUTCHES

There are two basic types of overrunning clutches currently in use in military helicopters: the sprag type and the ramp roller type. Two sprag types are shown schematically in Figure 7. In the type "A" design, a ribbon spring located between two sprag carriers keeps the sprags in contact with the inner and outer shafts. A garter-type spring accomplishes the same purpose in the type "B" design. Driving action is obtained by wedging the sprags between the inner and outer shaft races. During overrunning, the sprags slide on the inner or outer race. A feature of the type "B" design is the sprag abutment feature, which comes into play during a static overload. In an overload condition, the sprags contact each other, forming a solid unit which cannot rollover. Rollover under high static torque condition is a possible sprag failure mode for the type "A" design. The most common failure mode with sprag clutches is excessive wear, which occurs on the sliding sprag surface during overrunning. There have also been some instances of such components as the spring, carrier, or even the sprags themselves fracturing but these are relatively rare.

The basic operating principle of the ramp roller overrunning clutch is depicted in Figure 8. In the design shown, the innermost member is a cam shaped as an equilateral polygon with n sides, where n is equal to the number of rollers. The rollers are positioned in relation to each other by a carrier or cage member, which is spring loaded to impart a constant torque to the cage. This preload torque causes the rollers to touch the outer housing and cam and also forces the rollers to remain in contact under all operating conditions. When the input and output shafts are twisted relative to each other so as to wedge the rollers between the cam and housing, the freewheel unit is in the driving mode. When the opposite direction of torque is applied, the rollers will roll on the outer housing and slide on the cam, allowing the unit to overrun. Positive spring and plunger force is maintained throughout all operating modes by careful consideration of centrifugal loads and friction during the design of the mechanism. The camshaft contains circular-shaped relief grooves across the face of the cam. These grooves are provided for ease of assembly of the unit and have no other functional purpose. As with the sprag clutch, excessive wear of the rollers and cam is the most common failure mode for the ramp roller clutch. Other types of failure modes that have been experienced include cage wear and fracture, spring fracture, and roller fracture. These failure modes, however, are relatively infrequent.

There is also a third type of clutch, the spring clutch, which, although not presently used in any production aircraft, has shown great promise in several research and development programs. The principle of operation of the spring clutch is depicted in Figure 9. A spring of rectangular cross section is positioned between two concentric internal shaft diameters. The end coils of the spring are of a larger diameter than the central coils and are in contact with the bores of the shafts. When the two shafts are twisted relative to each other so as to tighten the spring,

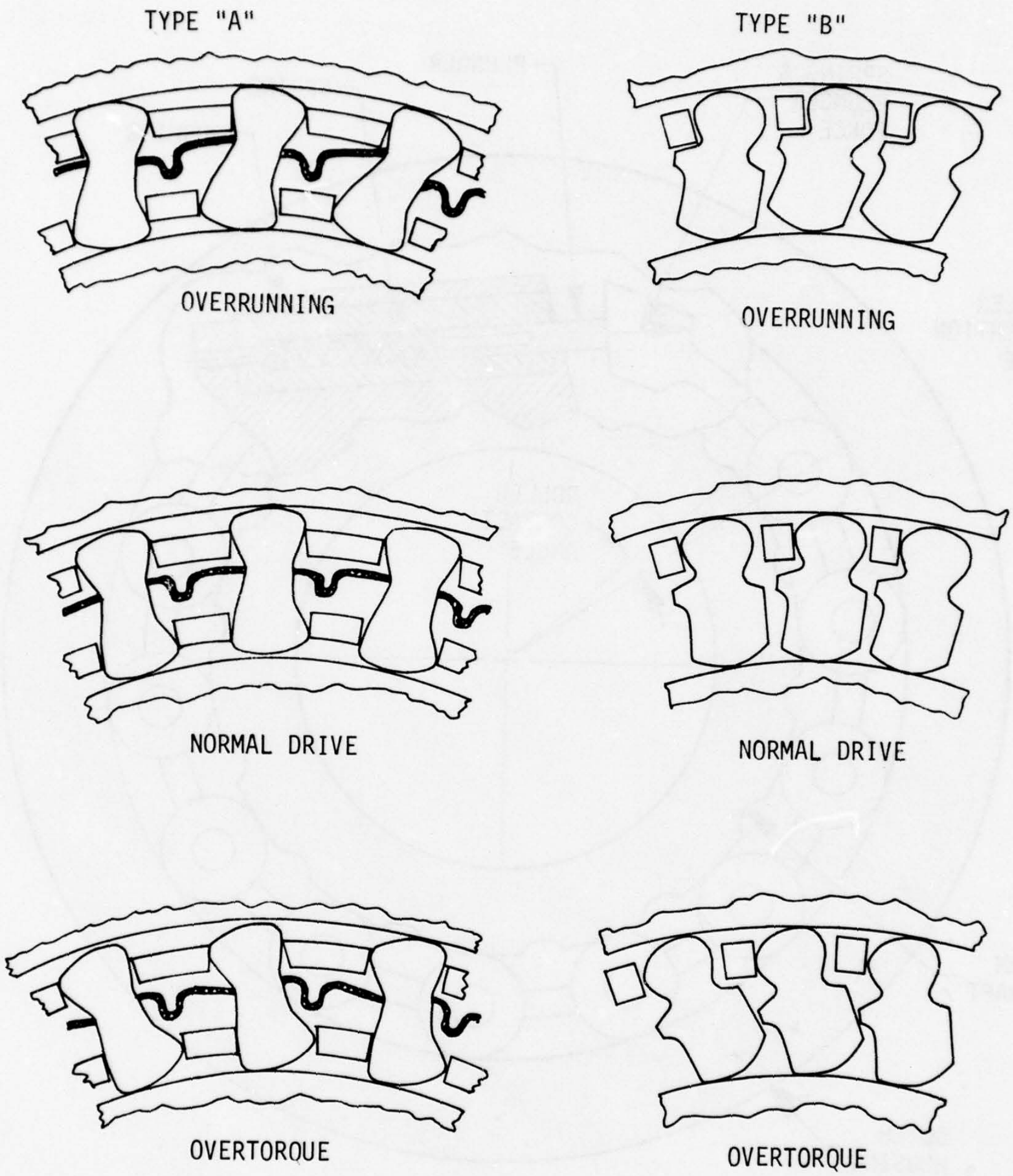


Figure 7. Sprag-Type Overruning Clutches.

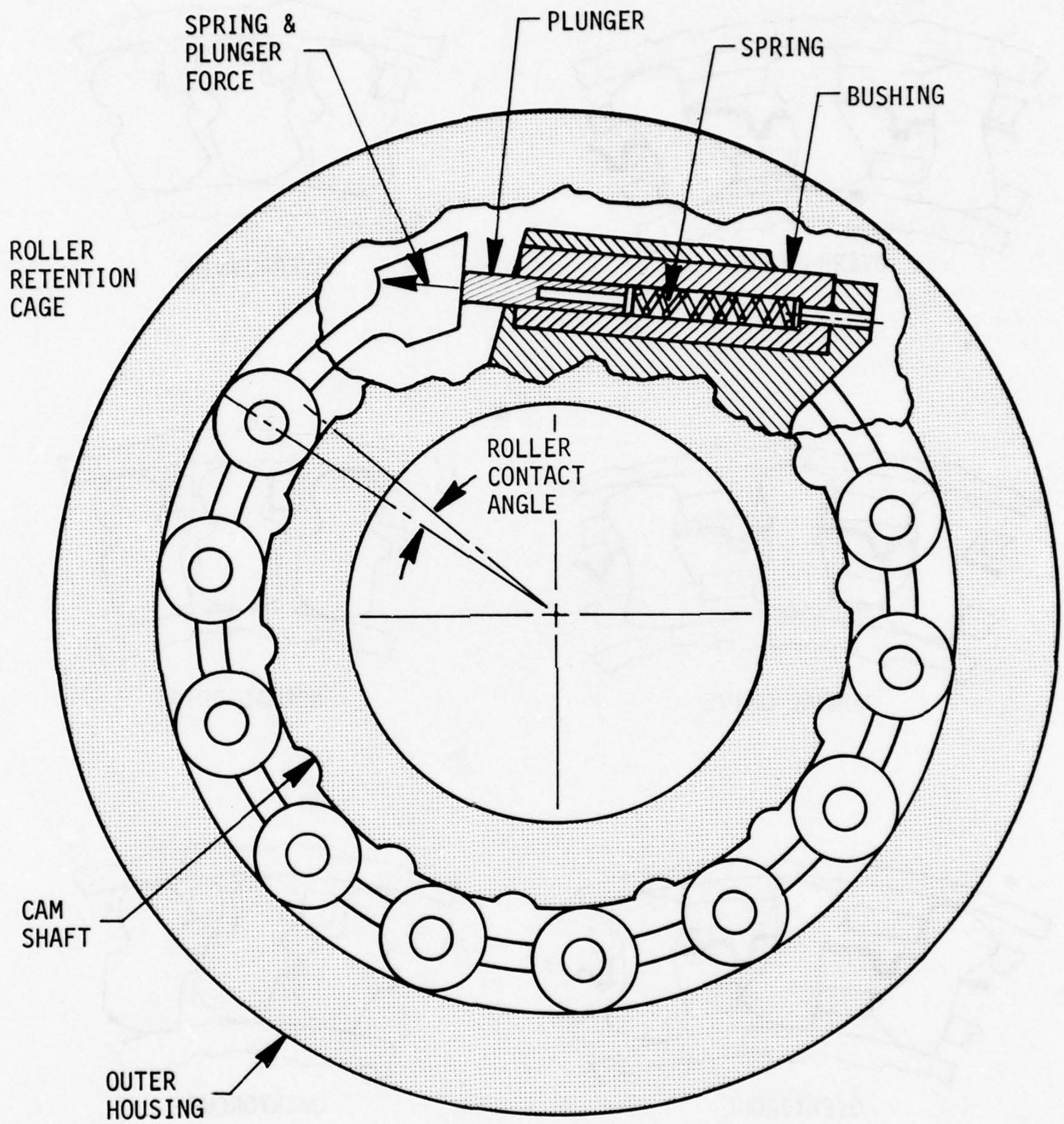


Figure 8. Ramp Roller-Type Overrunning Clutch.

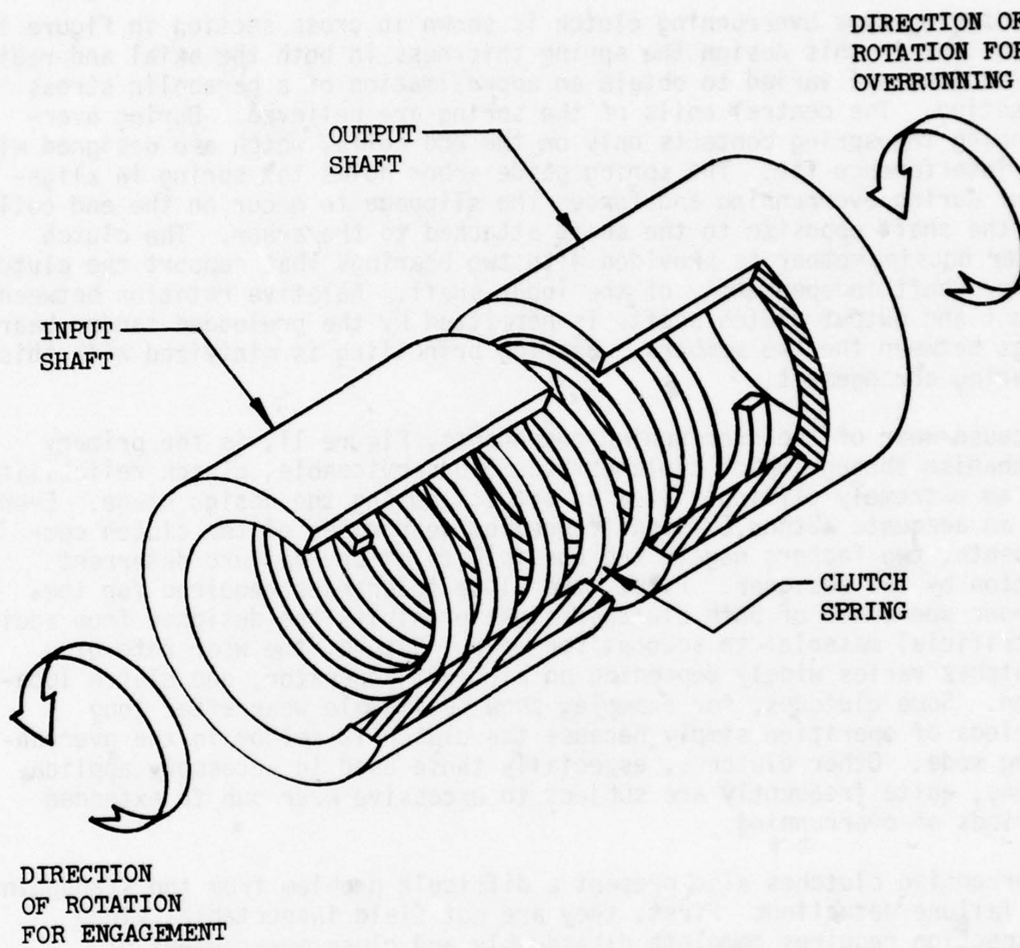


Figure 9. Principle of Operation, Spring Overrunning Clutch.

the end coils slip on the shaft bores. When the two shafts are twisted so as to unwind the spring, the spring expands and grips the shaft bores along its entire length. In this position the spring is able to transmit torque from one shaft across the gap to the other shaft.

The spring-type overrunning clutch is shown in cross section in Figure 10. Note that in this design the spring thickness in both the axial and radial dimensions are varied to obtain an approximation of a parabolic stress function. The central coils of the spring are relieved. During overrunning the spring contacts only on the end coils, which are designed with an interference fit. The spring guide arbor holds the spring in alignment during overrunning and forces the slippage to occur on the end coils of the shaft opposite to the shaft attached to the arbor. The clutch outer housing member is provided with two bearings that support the clutch outer shaft independently of the input shaft. Relative rotation between input and output clutch shafts is permitted by the preloaded tandem bearings between the two members. Bearing brinelling is minimized with this bearing arrangement.

Because wear of the overrunning components, Figure 11, is the primary mechanism through which clutches become unserviceable, clutch reliability is an extremely difficult item to predict during the design stage. Even if an adequate method existed to predict wear rates of the clutch components, two factors negate the possibility of any failure deterrent action by the designer. First, the close tolerances required for the proper operation of both clutch designs prohibits the designer from adding sacrificial material to account for wear. Second, the wear rate of clutches varies widely depending on aircraft, operator, and clutch location. Some clutches, for example, show negligible wear after long periods of operation simply because the clutch is seldom in the overrunning mode. Other clutches, especially those used in accessory applications, quite frequently are subject to excessive wear due to extended periods of overrunning.

Overrunning clutches also present a difficult problem from the standpoint of failure detection. First, they are not field inspectable, since inspection requires complete disassembly and close measurement of critical dimensions. Second, because they are usually placed in remote locations of the gearbox, the first indication of clutch failure is usually loss of torque from the engine, not chip detector light activation. With the relatively short overhaul intervals of helicopters presently in the Army inventory, clutch primary failure is generally not too frequent. At overhaul those clutch components subject to wear are usually replaced before the wear has progressed far enough to be a problem. With the advent of on-condition maintenance, however, it would not be surprising to see primary failure of clutches become a more common occurrence. To somewhat offset this potential problem in clutch reliability, future gearboxes should be designed with clutches that are field-replaceable units.

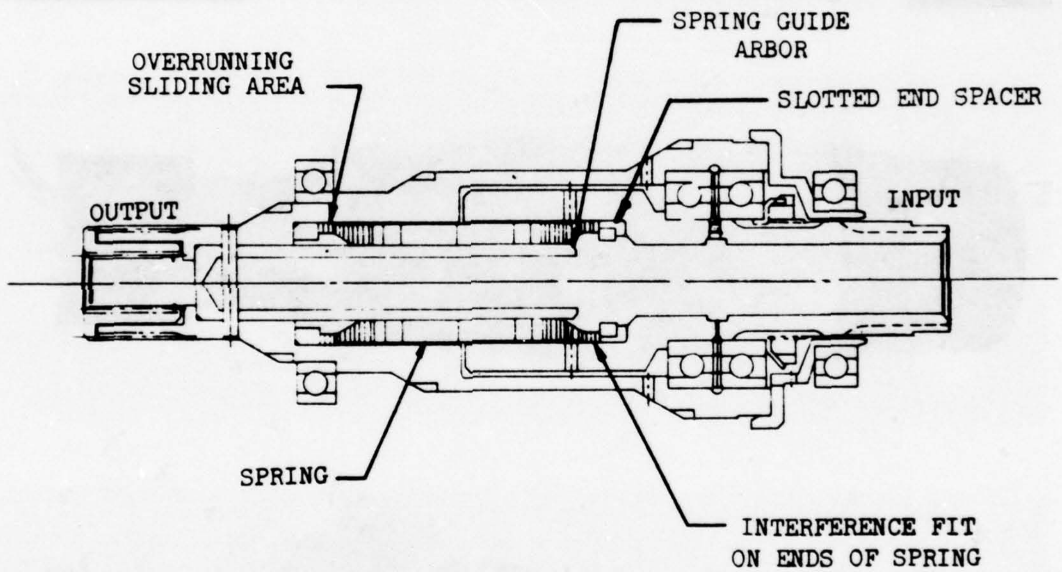


Figure 10. Spring Overrunning Clutch.

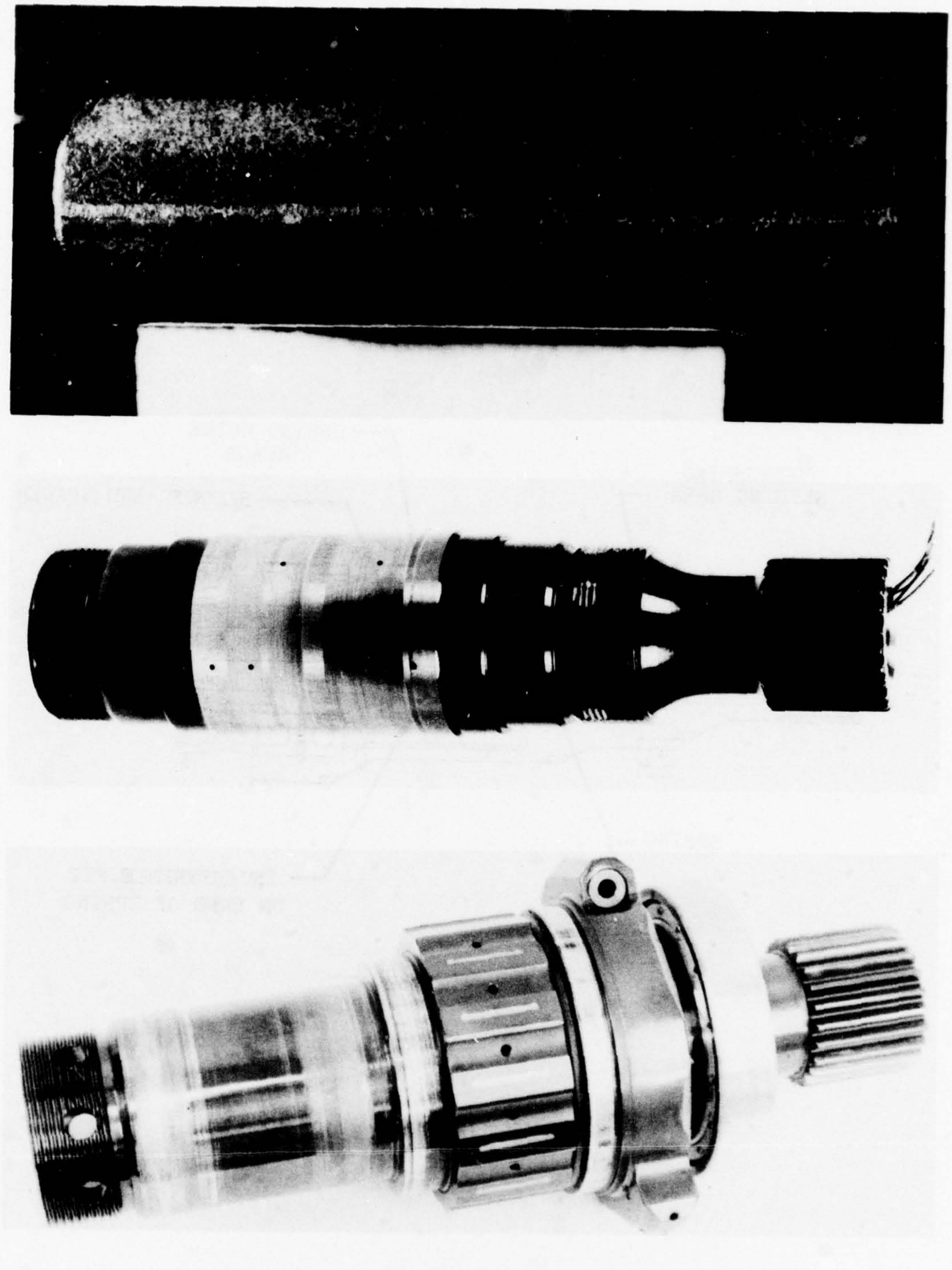


Figure 11. Overrunning Clutch Component Wear.

HOUSINGS

By far the most common failure mode in helicopter transmission housings is corrosion. Current helicopter gearbox housings are almost exclusively made of magnesium, which offers high strength-to-weight ratio with good castability. Unfortunately, magnesium has very little inherent corrosion resistance. The protective coatings that are applied to the housings do effectively prevent corrosion over most of the housing, but in areas of casting interface, e.g., around studs, corrosion remains a serious problem. Because the housing corrosion problem is inherent in the basic material, there is little the transmission designer can do about it. The best way to eliminate this problem is to develop an alternative to magnesium as a housing material. Although research into this area has by no means been extensive, some potential replacements for magnesium have been studied. Aluminum, which has far greater corrosion resistance than magnesium, has occasionally been used for small castings in place of magnesium. The problem with aluminum is that because of its relatively poor castability, too great a weight penalty must be paid to maintain the required minimum wall thickness. In recent years some research has been expended on the possibility of using fiber composites in place of magnesium. These materials, however, are at present too costly from both a manufacturing and material standpoint to be used for production housings. Perhaps the most promising candidate today for replacing magnesium housings is welded stainless steel. This concept is currently under development and has shown considerable promise in early design studies.

SHAFTS

There are three basic types of shafts used in current helicopter drive systems: external shafts (e.g., tail drive shafts, input shafts), internal shafts (e.g., quill shafts, gear shafts), and the main rotor shaft. The external shafts, which are usually made of aluminum, seldom, if ever, experience design-related failures. Failure modes encountered with these shafts are usually operationally induced. In general, internal shafts such as quill shafts are very reliable except for those shafts which have loose splines. If loose splines are not designed properly or supplied with adequate lubrication, severe fretting can occur, which may eventually lead to loss of transmission torque. Special attention to lubrication of loose splines during the design stage, however, can minimize the possibility of this type of failure. The main rotor shaft, of necessity, must be designed to be failure free, since failure of the main rotor shaft is invariably catastrophic. Because of the critical nature of the main rotor shaft, it is given much attention during the design stage. Consequently, main rotor shafts fail so seldom that they may be considered to have essentially a zero failure rate.

Supercritical drive shafts, which have been used particularly in tail drive shaft applications, offer some advantages over subcritical shafts. Chief among these from a reliability standpoint is the elimination of hanger bearings which often have a relatively high failure rate. The disadvantage of supercritical shafts is that very stringent balance requirements must be imposed. Otherwise large displacements incurred as the shaft passes through a resonance speed may damage the shaft.

COUPLINGS

There are several types of drive shaft couplings currently used in military helicopters, each with different operating characteristics and limitations. These types include the laminated disc or Thomas coupling, the flexible diaphragm or Bendix type, and the gear type. Another kind of coupling, the Bossler type, which has been used primarily on an experimental basis, will also be discussed here.

The Thomas coupling shown in Figure 12 is most commonly employed for misalignments of 1 degree or less. They accommodate very little relative axial motion. Among the advantages of Thomas couplings are simplicity, light weight, and low cost. Thomas couplings also require no lubrication. The most common failure mode of Thomas couplings is fretting of the steel laminates around the bolt holes. This problem can be avoided by using a coupling with a sufficiently large bolt circle diameter. Analysis of Thomas couplings is difficult at best. Hence, assistance from the manufacturer is usually sought before the final selection of any design.

The flexible diaphragm coupling, Figure 13, although used on the OH-5 and OH-6, is not seen on the more recent drive train designs. This particular type of coupling is capable of about the same order of magnitude of deflections as the Thomas coupling. The flexible diaphragm is, however, heavier than the Thomas coupling, and the monoball requires periodic lubrication. Fatigue fracture of the diaphragm stack is the most common failure mode of the diaphragm-type coupling. This problem may be somewhat mitigated by providing a ball spline to prevent the introduction of axial loads into the diaphragm elements. Often, however, vibratory forces due to imbalance and rotor vibration lead to false brinnelling of the ball track grooves, which can result in the introduction of axial loads.

Gear-type couplings, an example of which is shown in Figure 14, are usually used where high misalignment capability is required. This coupling is effective at high speeds for misalignments up to 3° steady and 6° transient. It also allows a relatively large amount of axial motion compared with other couplings. Unlike the other types, fatigue is not a problem with gear-type couplings. Overheating due to loss of lubricant, followed by plastic shear of the teeth, is the predominant failure mode for gear-type couplings. Hence, lubricant retention is of prime importance for high reliability. Guillotine slider seals and elastomeric boots are used in high-angle applications, while lip seals are used on low-angle applications.

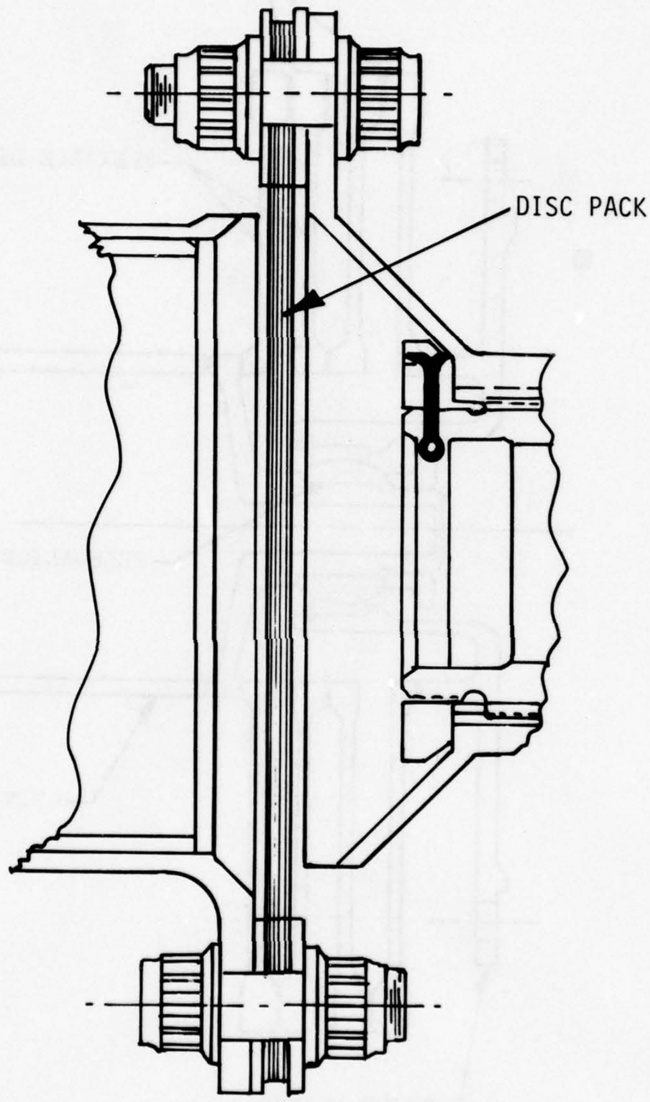


Figure 12. Disc Pack Thomas Coupling.

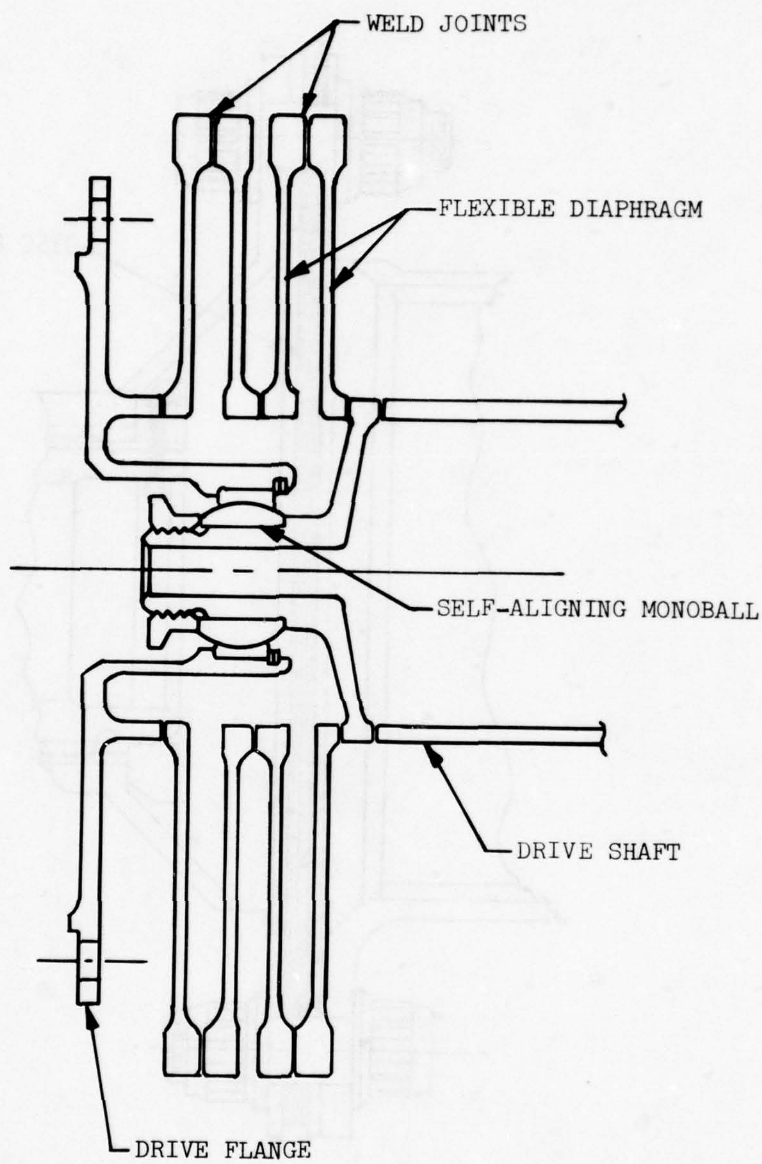


Figure 13. Flexible Diaphragm Coupling.

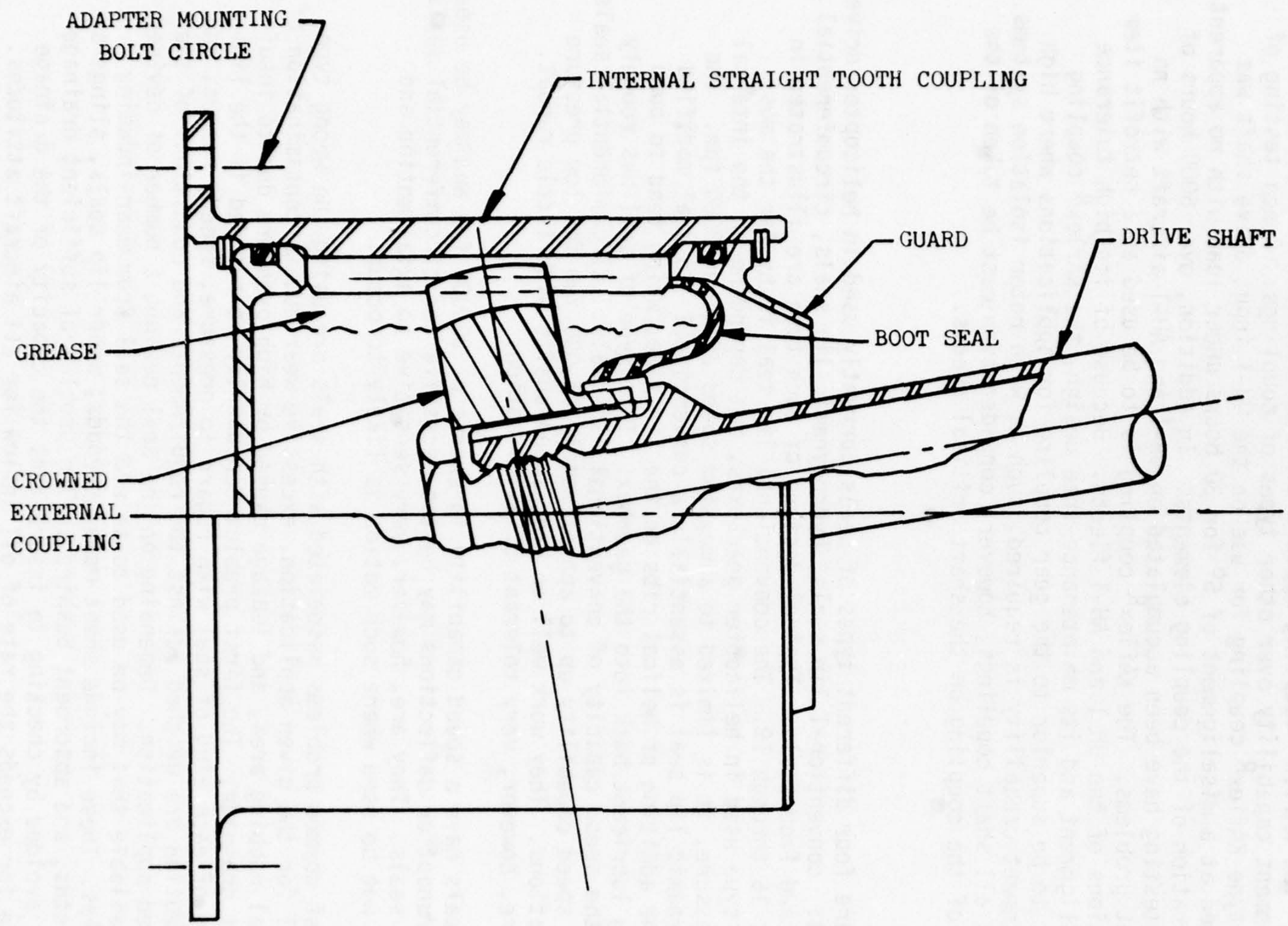


Figure 14. Gear Coupling.

The Bossler or KAflex^R coupling, shown in Figure 15, is a relatively new type of flexible drive shaft coupling that can accommodate both angular misalignment and axial deflection through a series of warped rectangular plates. The KAflex^R coupling appears to offer substantial improvement in misalignment capability over other types of couplings. Bench testing of a prototype KAflex^R coupling for use on the UH-1 input drive shaft was performed at a misalignment of 5^o for 30 hours under load with no apparent deterioration of the coupling elements. In addition, over 6000 hours of flight testing have been accumulated on UH-1 and AH-1 aircraft with no apparent problems. The KAflex^R coupling is to be used as a retrofit item on portions of the UH-1 and AH-1 fleets. Because of its high tolerance of misalignment and its maintenance-free design, the KAflex^R coupling appears to be superior to the gear coupling for applications where high misalignment capability is required, such as with rotor isolation systems. As with all shaft couplings, however, consideration must be taken of the effect of the coupling on the shaft critical speeds.

SEALS

There are four different types of seals currently used in helicopter drive systems: conventional lip seals, hydrodynamic lip seals, circumferential seals, and face seals. Typical designs of each type are illustrated in Figures 16 through 19. The conventional lip seal is by far the most common type used in helicopter gearboxes, but depending on the internal oil pressure, it is limited to a maximum speed of about 3000 fpm. The hydrodynamic lip seal is essentially a conventional lip seal modified with the addition of helical ribs on the air side, which tend to pump leaking lubricant back into the gearbox. This type of seal has roughly twice the speed capacity of conventional lip seals. Circumferential seals have a speed capability up to approximately 15,000 fpm for low pressure applications. They work well on high-speed shafts with little runout. They are, however, very tolerant of axial motion.

Face seals have a speed capability in excess of 20,000 fpm and may be used where runout or deflections may be too excessive for circumferential seals or lip seals. They are, however, very sensitive to axial motion and should not be used where such motion is likely to occur.

The most common problems associated with seals are using the wrong type of seal for the given application, excessive wear due to contamination of the seal rubbing area, and leakage caused by high pressure due to insufficient drainage. The first problem can usually be avoided if the limitations of each kind of seal with regard to pressure, speed, runout, and axial motion are weighed against the requirements and conditions of the proposed application. Depending on the seal design, a number of devices are available that may be used to shield the seal from wear-inducing particles. These include sheet metal shrouds, wiper lip seals, slingers, labyrinths, and absorbent bushings. The problem of sufficient drainage can be avoided by checking to insure that the capacity of the drainage passage far exceeds the rate of oil inflow for all aircraft attitudes.

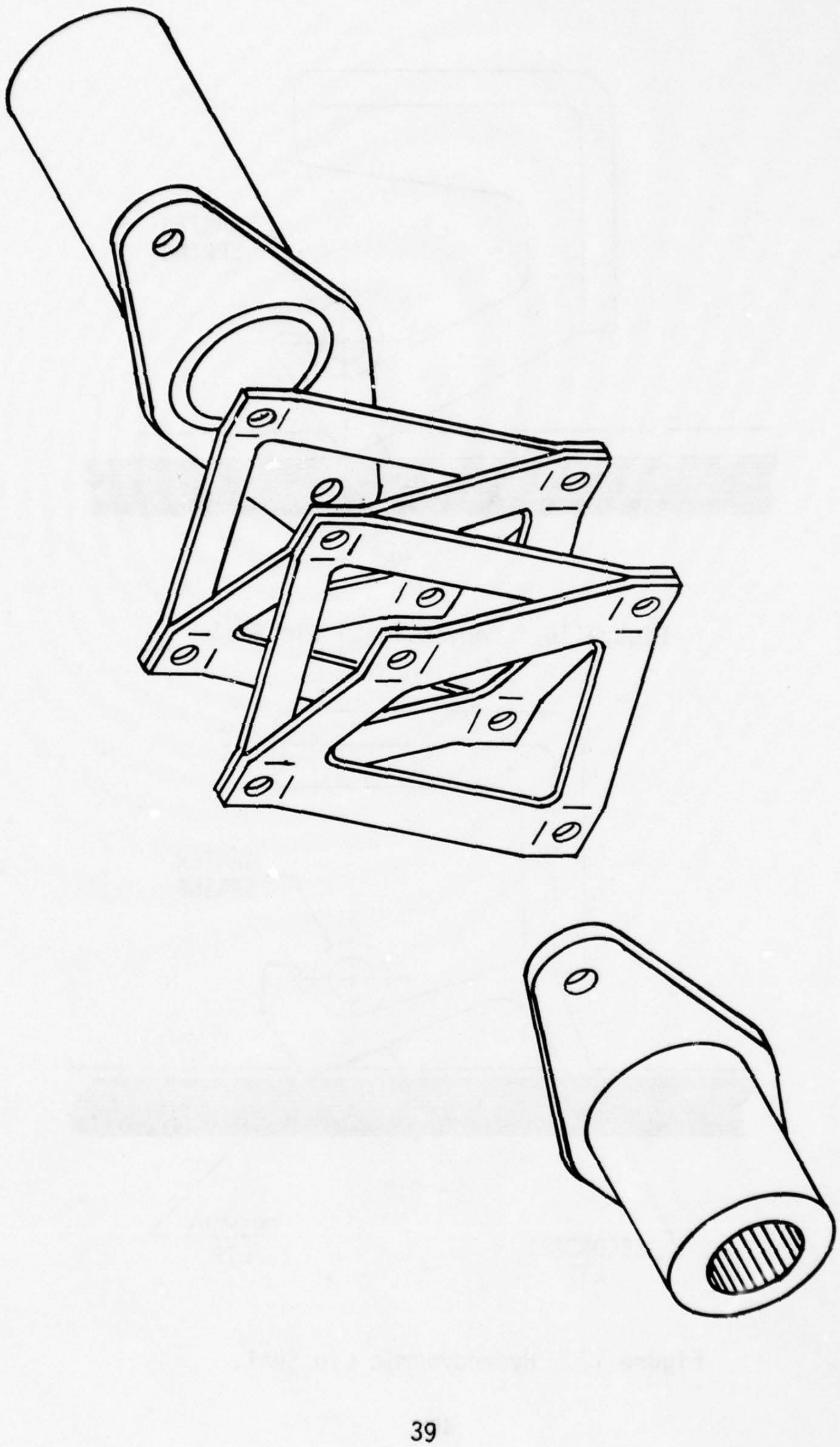


Figure 15. Bossler Coupling.

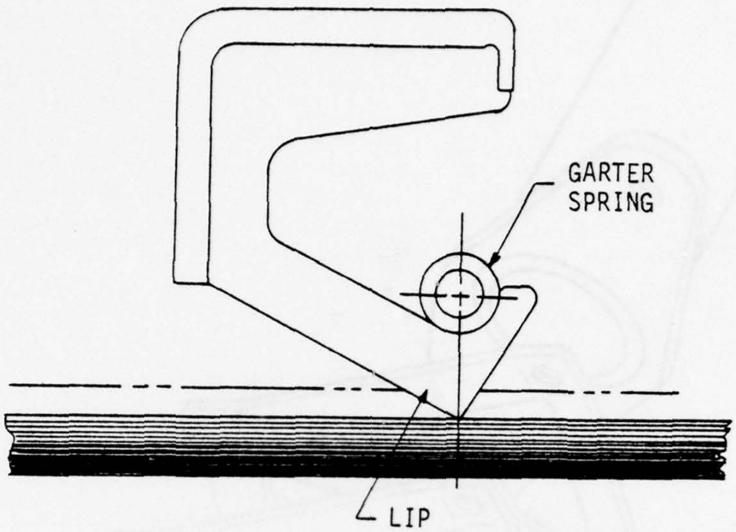


Figure 16. Conventional Lip Seal.

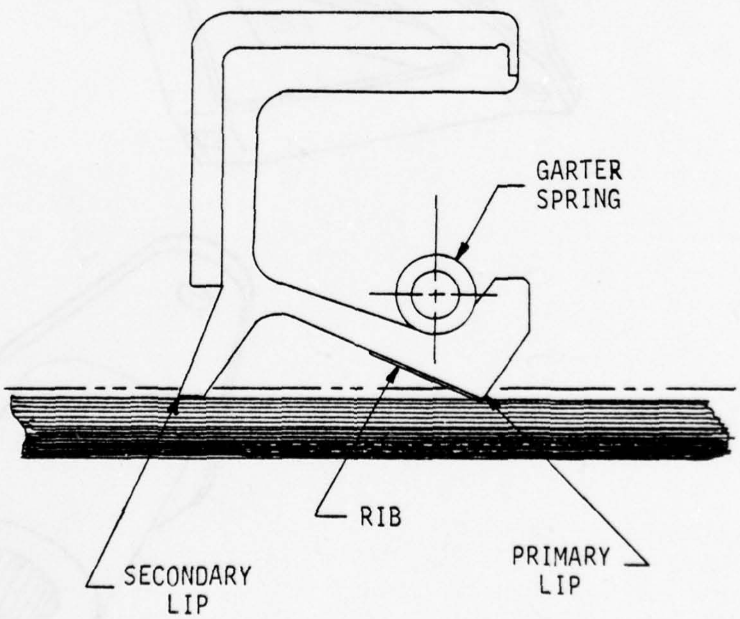


Figure 17. Hydrodynamic Lip Seal.

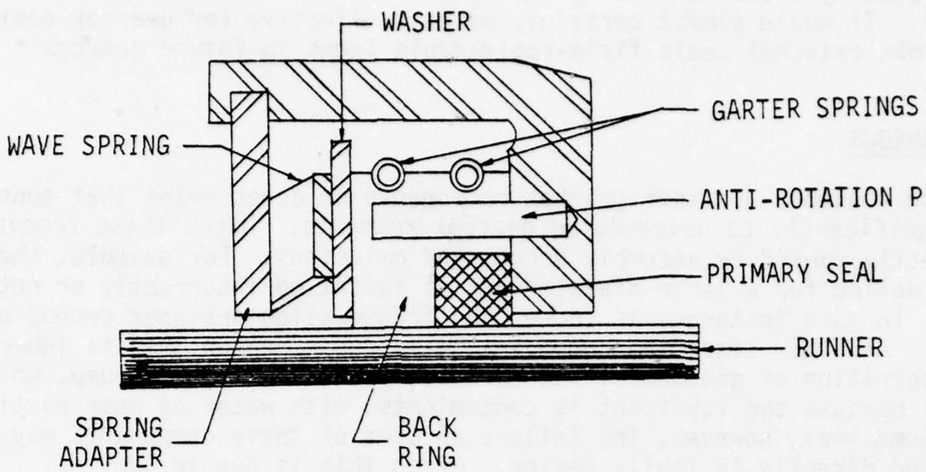


Figure 18. Circumferential Seal.

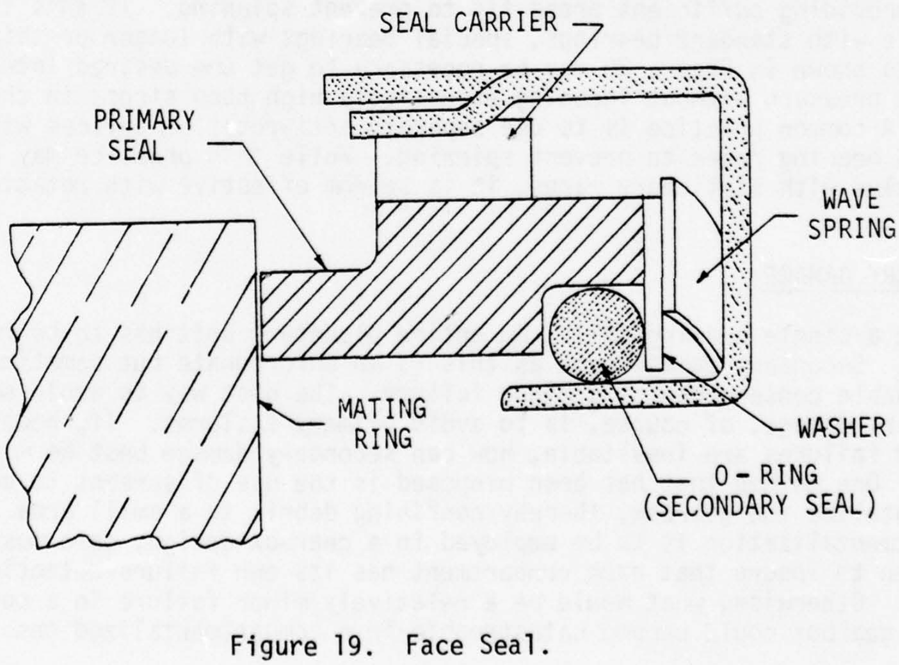


Figure 19. Face Seal.

Perhaps the greatest shortcoming in seal design is the fact that they are not, in general, field-replaceable items. The arguments usually made for not making them field replaceable is that such designs would increase weight and cost. Even considering these arguments, however, it is difficult to justify a $10 seal being the sole cause for a $20,000 gearbox overhaul. It would almost certainly be cost effective for gearbox designers to make external seals field-replaceable items in future gearbox designs.

MISCELLANEOUS

There are a number of minor gearbox components or accessories that contribute significantly to unscheduled gearbox removals. Often these removals are directly caused by assembly errors and omissions. For example, the locking device for a large-diameter nut is installed incorrectly or not at all. In such instances as these, the transmission designer cannot be faulted. At other times the component fails for a reason that is inherent in the operation of gearboxes. An example of this is the oil pump, which may fail because the lubricant is contaminated with water or wear particles. Sometimes, however, the failure of some of these components may be attributed directly to faulty design. Often this is due to lack of attention by the designer or to a misguided attempt to reduce weight. Such design deficiencies will not be discussed here. There is one design fault, however, which leads to the failure of so many retainers and spacers that it warrants further discussion. That is the problem of bearing races spinning on the shaft or housing and leading to excessive wear of these smaller components. If the wear is severe enough, this type of design oversight can lead to the failure of bevel gears, which are extremely sensitive to axial position. The best way to avoid this problem is by providing sufficient press fit to prevent spinning. If this is not possible with standard bearings, special bearings with longer or thicker races as shown in Figure 20 may be necessary to get the desired interference pressure without inducing excessively high hoop stress in the race. A common practice is to use separate anti-rotation devices with slotted bearing races to prevent spinning. While this practice may have some value with stationary races, it is seldom effective with rotating races.

SECONDARY DAMAGE

Because a single bearing fails, an entire planetary unit has to be replaced. Secondary damage such as this is an unfortunate but sometimes unavoidable consequence of a minor failure. The best way to avoid such secondary damage, of course, is to avoid primary failures. If, however, primary failures are inevitable, how can secondary damage best be minimized? One method that has been proposed is the use of screens to compartmentalize the gearbox, thereby confining debris to a small area. If compartmentalization is to be employed in a gearbox design, care must be taken to insure that each compartment has its own failure-detection device. Otherwise, what would be a relatively minor failure in a conventional gearbox could become catastrophic in a compartmentalized one.

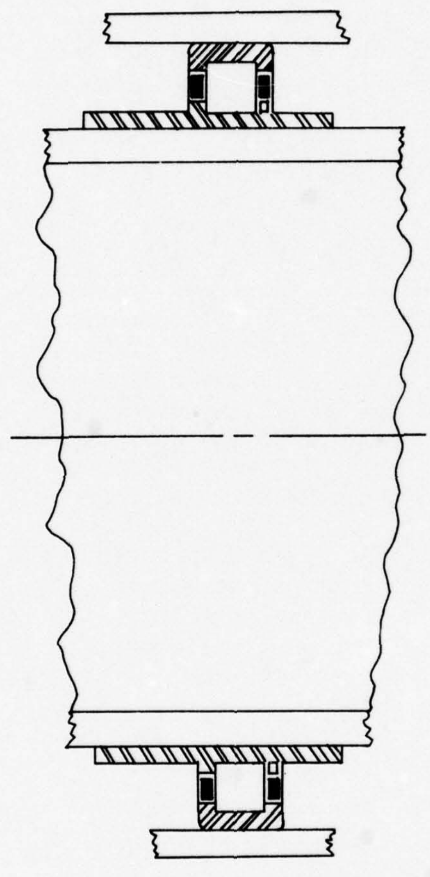


Figure 20. Roller Bearing With Elongated Inner Race.

Secondary failures resulting from lubricant system failure are especially serious, since often the entire gearbox is affected. Fortunately, most recent designs incorporate redundant lubrication systems so that a single pump failure is no longer that serious. Another lubricant-related problem is severe water contamination due to seal failure. This problem should be eliminated through redundant seals in areas where this type of leakage is possible, such as the main rotor shaft seal.

QUALITY CONTROL

Quality control has continuously been an important factor in drive train reliability problems. Poor quality control can easily negate an outstanding design effort, and significantly lower gearbox reliability. Although quality control is outside the area of responsibility of the gearbox designer, there are certain steps he can take that will make it more probable that the part meets the drawing requirements.

Quality control is the largest single cause for gear failure in helicopter gearboxes. There are two types of quality control problems that occur relatively frequently with gearing and therefore demand particular attention. The first of these is control of the root fillet radius. While inspection of this feature is not difficult on spur gears, it is extremely difficult on spiral bevel gears. Figure 21 shows a typical fillet radius control-related failure on a spiral bevel gear. As can be seen, the fillet was undercut at the origin of the failure, and this defect escaped detection by the inspector. One inspection method that may be employed to preclude this type of failure is to make plastic molds of a few teeth of each gear as shown in Figure 22. These molds may then be inspected by conventional radius checkers to insure that the root fillet radius meets drawing requirements.

The second problem associated with quality control of gears concerns control of case depth and hardness. Because non-destructive testing for this requirement is impossible, conformance to drawing requirements must be determined by inspection of a heat-treat sample. Since geometery is an important consideration in the carburization process, the sample should match as closely as possible the teeth of the gear. The best way to insure this is to make heat-treat samples by sectioning an actual gear of the type to be carburized. In this way, any adverse effect of geometry on case depth can be detected.

Bearings present a different type of quality control problem, since they are, for the most part, source inspected. Despite the fact that the helicopter manufacturer's inspector may randomly inspect some bearings, responsibility for the quality control of bearings rests largely with the bearing manufacturer. There are some measures, however, which the gearbox designer can take to minimize bearing quality control problems. First, the use of bearings with such features as integral threads, flanges, etc., should be minimized. Bearing manufacturers are not as accustomed to these types of features as they are to the basic bearing elements. Hence, there is a greater likelihood that errors will be made and not detected than if the bearing was free of such features. If a particular bearing manufacturer is especially susceptible to a certain quality control problem, he should be requested to pay closer attention to that problem. This approach can often lead to better quality control for gearings. The bearing drawing or specification should also be as complete as possible regarding inspection.

One particular bearing quality control problem deserves special attention. That is the problem of dents or indentations of bearing elements prior to service. Although there are standards that govern the size and depth of

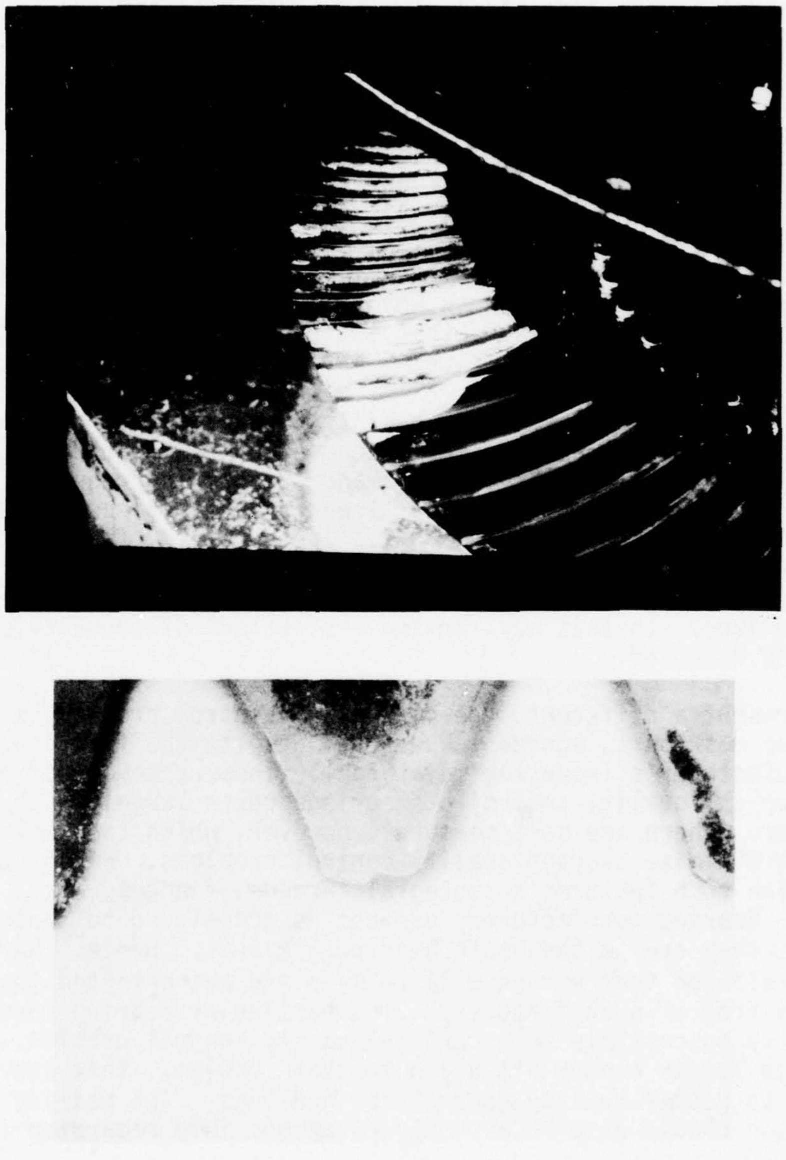


Figure 21. Gear Tooth Failure Caused by Fillet Radius Control Problem.

these nicks, there is some evidence that bearing lives could be increased if these standards were more stringent. It is possible, for example, that nicks and dents prior to service are more likely to lead to bearing spalling than indentations caused by lubricant contamination during service. Hence, it might be advisable to tighten quality control standards governing prior-to-service indentations as well as to establish practices for those handling bearings during gearbox buildup, which will minimize the possibility of nicks.

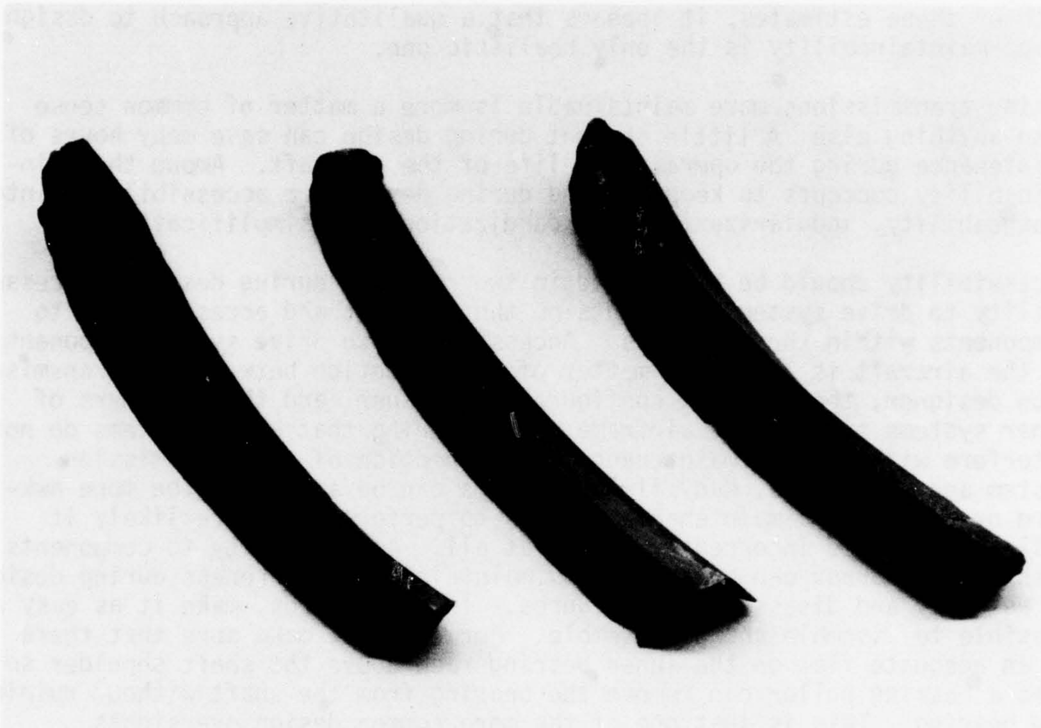


Figure 22. Inspection Molds for Spiral Bevel Gears.

MAINTAINABILITY

As difficult as it is during design to quantify reliability accurately, maintainability is even more difficult to quantify, perhaps impossible. The most common unit for measuring maintainability is maintenance manhours per flight hour (MMH/FH). The maintenance manhour burden for any system depends not only on the time required to perform the maintenance, but also on how many times the maintenance must be performed. Hence, in order to make an estimate of the maintenance manhour burden during design, the designer must first estimate its reliability. Given the difficulty of each of these estimates, it appears that a qualitative approach to design stage maintainability is the only realistic one.

Making transmissions more maintainable is more a matter of common sense than anything else. A little thought during design can save many hours of maintenance during the operational life of the aircraft. Among the maintainability concepts to keep in mind during design are accessibility, interchangeability, modularization, standardization, and simplification.

Accessibility should be considered in two respects during design: accessibility to drive system components on the aircraft and accessibility to components within the gearboxes. Accessibility to drive system components on the aircraft is largely a matter of communication between the transmission designer, the aircraft configuration manager, and the designers of other systems such as the airframe. By insuring that other systems do not interfere with routine maintenance and inspection of the transmission system and vice versa, many field problems can be avoided. The more awkward or difficult a maintenance task is to perform, the more likely it will be performed incorrectly or not at all. Accessibility to components within the gearbox can be assured by maintaining an awareness during design of assembly and disassembly procedures. In other words, make it as easy as possible to assemble and disassemble. For example, make sure that there is an adequate flat on the inner bearing race above the shaft shoulder so that a bearing puller can remove the bearing from the shaft without ruining the bearing. This is just one of the more common design oversights.

Interchangeability is another way to simply and conveniently reduce maintenance costs. The use of interchangeable parts can significantly reduce spares requirements as well as considerably simplify maintenance. Among the items that lend themselves well to interchangeability are tail drive shaft sections, drive shaft flanges, large diameter nuts, spacers, certain bearings, input and output intermediate gearbox housings, and all input components of twin engine helicopters.

Standardization is yet another concept that can significantly simplify maintenance tasks as well as reduce the time required for them. Standardization is simply the use of standard size nuts, bolts, etc., to the maximum extent possible, thereby reducing the number of special tools required to perform maintenance. The best way for the transmission designer to incorporate maximum standardization is to familiarize himself with the standard U. S. Army aircraft repairman's tools kit and to use hardware compatible with it.

Modularization is simply the compartmentalization concept, discussed earlier, carried one step further by making the compartments removable from the gearbox as complete subassemblies. Figures 23 and 24 show exploded isometric and cross-sectional views respectively of a six-module design of a CH-54 main transmission. This particular arrangement was one of several investigated as part of an earlier program conducted for the Eustis Applied Technology Laboratory. This study showed that modularization is highly effective in reducing transmission maintenance costs. Since debris from a failure is confined to a particular module in a modularized design, only one module need be removed and sent to depot for overhaul instead of the entire gearbox. This leads to substantial cost savings at depot and reduced aircraft down time in the field. Care should be taken during the design of a modularized transmission that the modules are easily removable through standardization of attaching hardware. Modularization is a very important concept in maintainability improvement strategy and should be seriously considered for any gearbox operating in excess of 1500 horsepower.

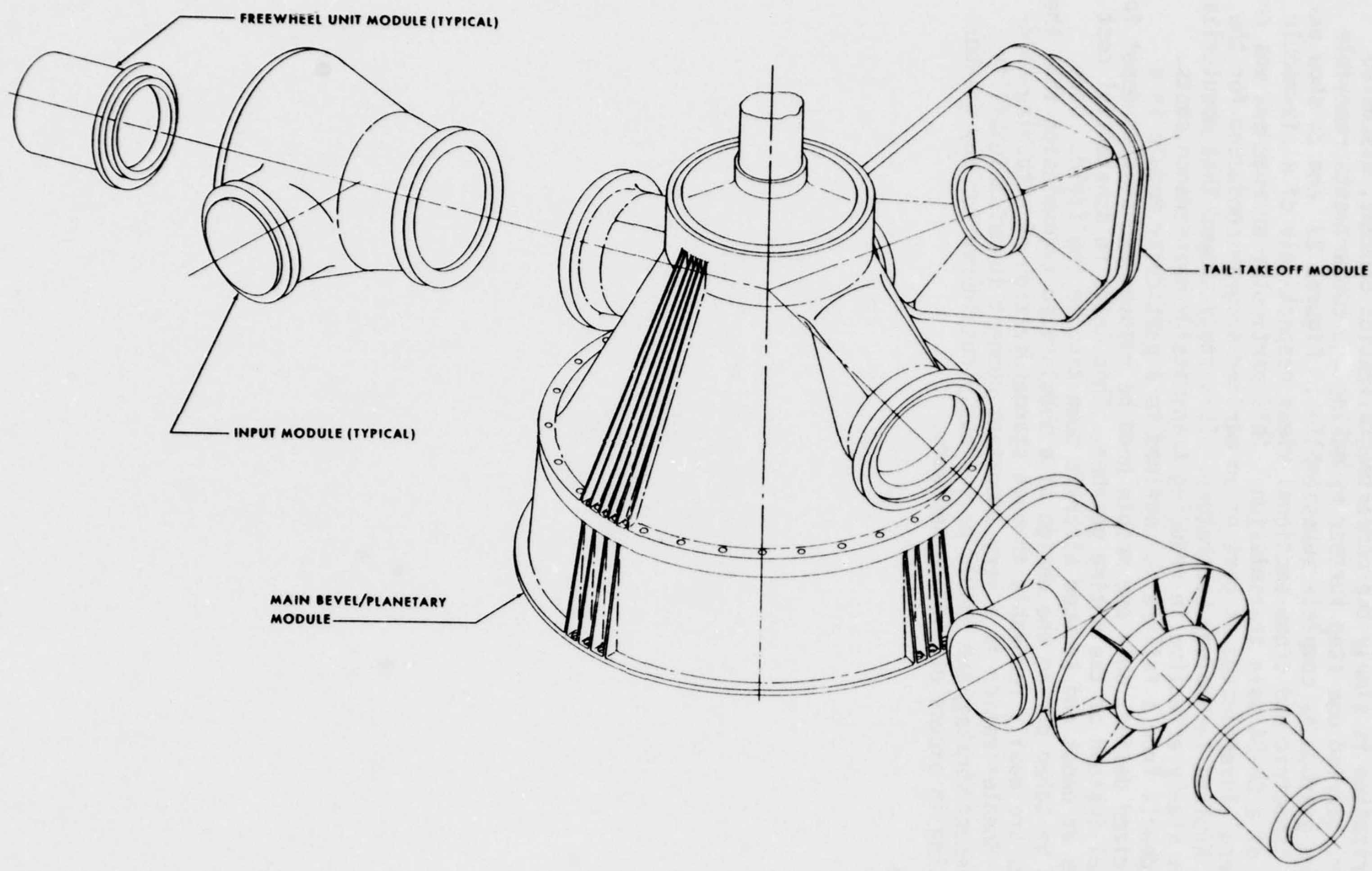


Figure 23. CH-54 Modularized Main Gearbox Isometric.

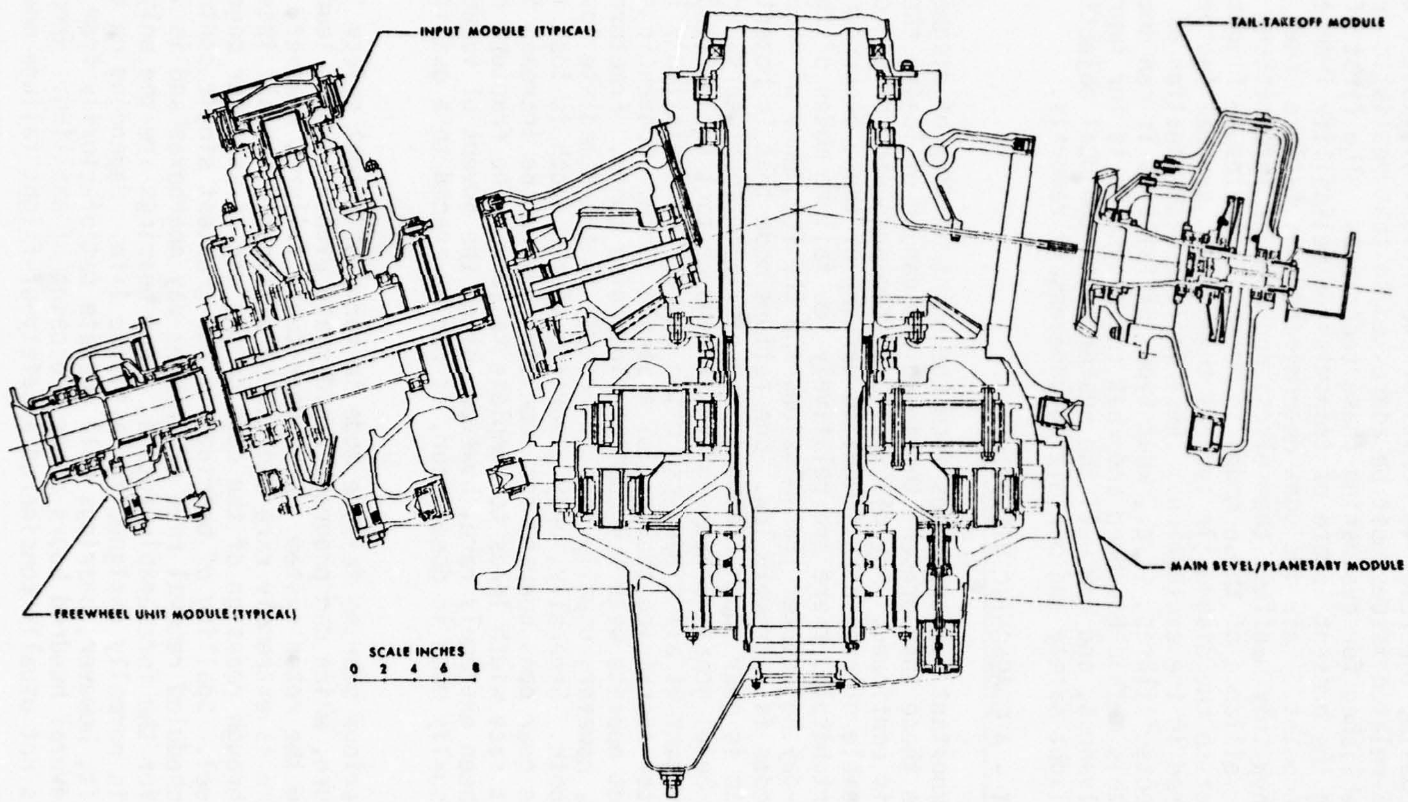


Figure 24. CH-54 Modularized Main Gearbox Cross Section.

DIAGNOSTICS

Before discussing the relative merits of the various diagnostic techniques, a number of related issues must be addressed so that realistic criteria can be established for evaluating these techniques. The first of these is defining the present state of transmission reliability from the diagnostic standpoint. This includes determining what failure modes can be expected, how they manifest themselves, and whether intermittent or continuous surveillance of these modes is necessary to insure flight safety. With respect to the diagnostic systems themselves, several factors must be considered in the evaluation. These include determination of how the system detects failures, (i.e., what types of failures it can detect), how effective this method has been and what the prognosis is for improving the effectiveness, and how well the system meets the dual objectives of insuring flight safety and minimizing unnecessary removals.

RELIABILITY - A DIAGNOSTIC VIEWPOINT

The most important failure modes from the point of view of diagnostic systems are those that present the immediate danger of losing the aircraft if flight is continued. Any diagnostic system proposed for use on aircraft must be capable of providing immediate warning of these occurrences to the pilot. Fortunately, there are relatively few failure modes of this nature in present-day helicopter transmissions and the frequency of occurrence of these modes is extremely low. One failure mode that is potentially catastrophic is gear tooth fracture, especially in spur gears. Helical and spiral bevel gears, because of their high contact ratios (two or more teeth in contact at all times) can often operate for relatively long periods after sustaining the loss of a single tooth. Conventional spur gears cannot operate with the complete loss of a tooth. Fracture of spur gear teeth, however, usually does not result in the immediate loss of the complete tooth. Generally, only a portion of the tooth is lost initially so that the gear does operate for some time before the increase in stress due to lost face width leads to complete failure. The fracture of gear teeth has been extremely rare, however, since the advent of vacuum-melt steels. Usually when it does occur, it can be traced to a quality control error.

The most serious bearing failure mode in terms of flight safety is bearing cage fracture, which can progress rapidly and within seconds lead to loss of power to the rotor system. Like gear tooth failure, however, bearing cage failure is extremely rare and can be eliminated for all intents and purposes through redesign of the cage or the use of stronger cage materials such as steel. Spalling of bearings is the greatest single contributor to the unscheduled removal rate of present-day gearboxes and is likely to remain so for the foreseeable future, since bearings are the only component that is normally designed for a finite life. Depending on the speed of the shaft, however, bearings will operate satisfactorily from several hours to several hundred hours after the onset of spalling. Hence, bearing spalling is not usually considered a safety-of-flight failure mode.

Although the above discussion is by no means complete, some statements may be made regarding the present state of gearbox reliability and its relationship to diagnostics. First, given the paucity and low frequency of safety-of-flight failure modes, an on-condition maintenance policy may be instituted regardless of the type of diagnostic system employed. Second, this policy combined with the relatively high reliability of present-day transmission components should result in MTBR's on the order of 5000 hours for new generation aircraft such as the UH-60A BLACK HAWK. This presents a challenge to the diagnostic system in that the achievement of such high MTBR's depends largely on the diagnostic system keeping unnecessary removals to an absolute minimum without sacrificing flight safety. In order to maintain flight safety, the diagnostic system must be able to detect such failure modes as gear tooth breakage, however rarely they occur, and bearing spalls as early as possible to minimize the secondary damage due to metal contamination resulting from such failures. From this statement, it can readily be concluded that the diagnostic system employed must be able to detect the presence of relatively large pieces of metal debris in the gearbox lubricant.

The frequency of diagnostic surveillance is another issue that must be addressed at this time, since the choice depends on the current state of gearbox reliability. Obviously, it is desirable to have continuous monitoring of such failure modes as gear tooth breakage. On the other hand, such failure modes as bearing spalling, because of their slow onset rate, require only periodic monitoring. Chip detectors have always been the primary diagnostic technique used in helicopter transmissions and are likely to remain so. Unfortunately, while chip detectors are very effective in detecting safety-of-flight failure modes, they have caused an inordinate number of mission aborts through false indications. In view of this, it has been suggested that chip detector monitors be removed from cockpits, and that the checking of the chip detectors made a post-flight maintenance responsibility. The justification for this approach is that failure modes that can result in almost immediate loss of the aircraft have essentially been eliminated from helicopter gearboxes. Therefore, continuous monitoring of the chip detectors is unnecessary. Removing the indicators from the cockpit would substantially decrease the mission abort rate, to which false chip light indications have largely contributed.

Although the logic of this argument is sound, some other factors must be considered. First, during the course of this program, a tour was made of Army operational facilities at Fort Rucker, Alabama, and Fort Campbell, Kentucky. During this tour, the idea of removing chip detector indicators from the cockpit was presented to a number of pilots at these bases. These pilots were unanimous in their opposition to it. Although these pilots were well aware of the high percentage of false chip indications, they felt that the information conveyed by chip light indicators should be available to the pilot at all times. Other questions arise as to what extent gearbox safety-of-flight failure modes have been eliminated and how often have chip detectors diagnosed these failures early enough to save the aircraft. With respect to the first question, while it is true that vacuum-melt steels have made the possibility of such failures as gear tooth breakage remote, the possibility of undetected quality control errors leading to such failures remains. The second question is more difficult to address,since no statistics on the success of chip indications preventing catastrophy are available. Even if this information was available, however, how does one trade off between mission aborts and human lives? For example, should chip detector indications be removed from the cockpit where such action might save a thousand aborts but cost one life? It would seem that that judgment should be left to the pilot.

FAILURE DETECTION METHODS

Diagnostic techniques for use in helicopter gearboxes can be divided into two basic groups: debris analysis and vibration analysis. The debris analysis methods include particle count techniques, chip detectors, SOAP (Spectrometric Oil Analysis Program), and filter checks. Vibration analysis consists of the monitoring of certain frequency bands where changes in amplitude indicate failures or impending failures.

The following paragraphs present discussions of the strengths and weaknesses of the various methods.

Chip Detectors

By far the most commonly used failure detection device in helicopter gearboxes is the magnetic chip detector. In its simplest form, the chip detector is a magnetic plug that collects ferrous debris on a powerful two-pole magnet. This type of chip detector must be removed and visually inspected to determine component condition. Current transmissions use electric chip detectors that are remotely monitored and checked periodically by a continuity test. These chip detectors can be procured with a variety of features such as a self-closing feature for quick removal without lubricant drainage, and the inclusion of a high-temperature warning switch.

The two types currently used in most transmissions are the full-flow and the sump-mounted plug, shown in Figure 25. The full-flow chip detector is usually installed in a lubrication line leading to the pump and monitors all the lubricant that is continuously circulating in the transmission. A strainer incorporated with the chip detector retains large particles, thus eliminating the need for a separate pump inlet screen. The sump-mounted chip detector magnetically attracts particles that settle to the bottom of the sump. Its efficiency is less than the full-flow chip detector,since it depends mostly on magnetic attraction to capture debris particles, while the full-flow chip detector has the advantage of pump pressure carrying the debris particles to it.

Chip detector sensititivity depends on the gap width, gap area, the type of magnetic circuit, and the shape of the electrodes. In general, smaller gap width and areas are most sensitive as are closed (versus open) magnetic circuits and sharp(versus rounded) electrodes.

The principal criticism of chip detectors has been the fact that although they have a good flight safety record, they are responsible for large

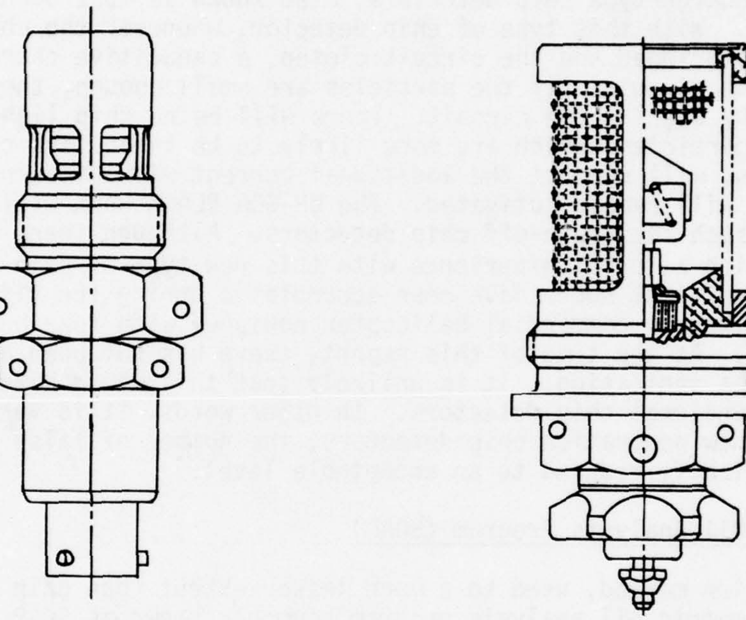


Figure 25. Typical Transmission Chip Detectors.

numbers of mission aborts and unnecessary gearbox removals due to false light indications. While this criticism is justified, there are some extenuating circumstances that must be considered. First, the bad record of chip detectors with respect to false indications is based largely on the early generation chip detectors used on the UH-1 aircraft. Because of the relatively poor design of the electrical connections, these chip detectors often shorted out, thus producing a false chip light activation. With recent designs, the improved connection has dramatically lessened the probability of this happening. The other primary cause of false indications has been the bridging of the chip detector gap with extremely fine particles due to the normal wear of gearbox dynamic components. To combat this problem, chip detector designers have recently introduced capacitive-discharge-type chip detectors, also known as fuzz burn-off chip detectors. With this type of chip detector, whenever the chip detector gap is bridged and the circuit closed, a capacitive charge is sent through the circuit. If the particles are small enough, they will burn up, thereby opening the circuit. There will be no chip light activation. Larger particles, which are more likely to be indicative of significant problems, will conduct the additional current without burning and the chip light will remain activated. The UH-60A BLACK HAWK will be equipped with such fuzz burn-off chip detectors. Although there has been little production aircraft experience with this new type of chip detector, several hundred flight hours have been accumulated during the flight testing of a new Sikorsky commercial helicopter equipped with fuzz burn-off chip detectors. At the time of this report, there has not been a single false chip light indication. It is unlikely that this would have been the case with conventional chip detectors. In other words, it is very possible that with the new generation chip detectors, the number of false indications will be dramatically reduced to an acceptable level.

Spectrometric Oil Analysis Program (SOAP)

Another detection method, used to a much lesser extent than chip detectors, is the spectrometric oil analysis program commonly known as SOAP. The SOAP technique consists of performing a spectrometric analysis of a gearbox oil sample to determine metallic content. The SOAP sample is taken from a subject gearbox as soon as possible after a flight to prevent metallic particles from settling out of the lubricant. A portion of the sample lubricant and an oil standard with known metallic content are placed on a film plate to record the wave length of the different elements. The exposed film is then placed in an optical comparator, which permits comparison of the widths of the lines representing the various elements. This enables the technician to determine the contaminant levels in the SOAP sample.

The SOAP technique has been used to a limited extent by commercial operators, the Army (ASOAP), and the Navy (NOAP). The success has been somewhat limited. There appears to be two basic problems with SOAP. First, the proper threshold level for gearbox removal has been difficult to establish. It appears that although some gearboxes exhibit high iron content levels, the gearbox turns out to be perfectly acceptable when it is disassembled and inspected. Other gearboxes have exhibited fretting failures, although the iron content has been relatively low. The Army, in particular, because of its large number of flight facilities, has experienced logistics problems with its ASOAP program. This is due to communication problems between the ASOAP laboratory and the various operational activities, and has sometimes led to needless gearbox removal.

A more serious problem, perhaps a more pertinent one as far as the future of SOAP is concerned, is the advent of superfine oil filters with the capability of removing all particles greater than 3 microns from the lubrication system. Such filters have undergone considerable development and the only problem remaining is the requirement of a larger space allocation than that of conventional filters. If the larger space is available, it seems certain that they will become standard equipment within a few years because of the great impact they have in improving bearing life. The problem this raises with SOAP is that the technique cannot be used to analyze such fine particles; hence, the large-scale incorporation of superfine filters will be tantamount to ending the practicality of SOAP.

Oil Debris Monitoring (Particle Count)

This technique, like SOAP, is not an in-flight monitoring technique. It consists essentially of determining the distribution of particle sizes within the gearbox lubricant. The primary problem with this method is that the relationship between particle size distribution and failure modes is largely unknown. Hence, this method may result in a large number of false removals and/or missed failures because the threshold for gearbox removal is mostly guesswork. This may be a moot point, however, since superfine filters would also render this method impractical.

Filter Checks

Filter checks have been recently employed during the development of superfine oil filters as a supplement to chip detectors. With this technique, a relatively coarse screen (about 80 microns) is placed around the superfine filter element. This screen, which traps only large particles, is inspected periodically and after chip light activation to aid in the determination of whether or not a failure has indeed occurred. The inspection of the debris is done visually with a simple means of magnification to determine the type of the debris trapped by the mesh. Although filter checking cannot be used as the primary diagnostic system, it has potential to be a valuable supplement to chip detectors or to another primary diagnostic system.

Vibration Analysis

The development of failure detection by vibration analysis has been the major thrust of a number of programs to develop an AIDAPS (Automatic Inspection, Diagnosis, and Prognosis System) for helicopter drive systems. Various techniques including low-frequency analysis, high-frequency analysis, narrow band spectrum analysis, and shock pulse monitoring have been evaluated and some of the more promising techniques have been tested in an actual helicopter transmission. Testing to date has been largely conducted with discrepant components implanted in the gearbox in order to define differences in vibration signatures between assemblies with defective parts and those without. There has been no extensive study on a fleet of helicopters that would provide an indication of the success rate of such a system.

The instrumentation and electronics hardware required for an AIDAPS are of necessity very sophisticated, a fact that could jeopardize the reliability of the system should it ever be widely employed. Another problem found with the application of AIDAPS to helicopter transmissions is the fact that vibration signatures of helicopter gearboxes are very maintenance sensitive and vary considerably from aircraft to aircraft, even among like models. Hence, in order to incorporate such a vibration detection system, a large amount of data would have to be assembled to establish vibration limits for gearbox removal. Thus, not only would the hardware itself be expensive (probably greater than $10,000 per aircraft), but also the research and development costs required to develop an AIDAPS so it could be practically employed on production aircraft would probably be prohibitive.

EVALUATION

From the above discussion, a number of conclusions can be drawn regarding the best policy to adopt with respect to drive system diagnostic systems. First, it is <u>not</u> recommended that investigations of SOAP or particle count techniques be pursued to a greater extent than they now are. In all likelihood, both of these techniques will soon be rendered obsolete by the incorporation of superfine filters. Second, before committing any large amounts of resources to the development of AIDAPS, time should be allowed to evaluate how effective fuzz burn-off chip detectors are in reducing false indications on the UH-60A BLACK HAWK. There is no sense in spending large amounts of R&D funds developing an expensive and complicated new system when it is likely that a much cheaper and simpler existing system will do the job just as well, if not better. Some may point out that chip detectors only provide after-the-fact indication of failures. However, given the fact that little is known about the symptom/failure relationship before failures occur, it is unlikely that any system no matter how sophisticated could give reliable advance warning of failure in the foreseeable future. Another justification often cited for supporting the development of AIDAPS is that chip detectors do not point out exactly which component failed within the gearbox. For helicopter gearboxes, however, this information is of academic interest only. Any failure that occurs inside a helicopter gearbox requires the removal of either the entire gearbox or the entire module in a modularized gearbox. Since the defective gearbox or module will be completely disassembled and inspected at depot anyway, there is no cost saving in knowing at the time of failure exactly which component failed. This type of information is useful only for failures that can be repaired on the aircraft, of which there are very few in helicopter gearboxes.

The most promising approach to diagnostics at this time appears to be the system illustrated in Figure 26. This system incorporates both sump-mounted and flow-through fuzz burn-off chip detectors supplemented by filter inspection. This system has many advantages over the other candidates. First, it is simple and inexpensive. Second, it is a proven system with respect to flight safety. Third, if early experience with fuzz burn-off chip detectors is any indication, it will be very reliable and produce very few unnecessary gearbox removals.

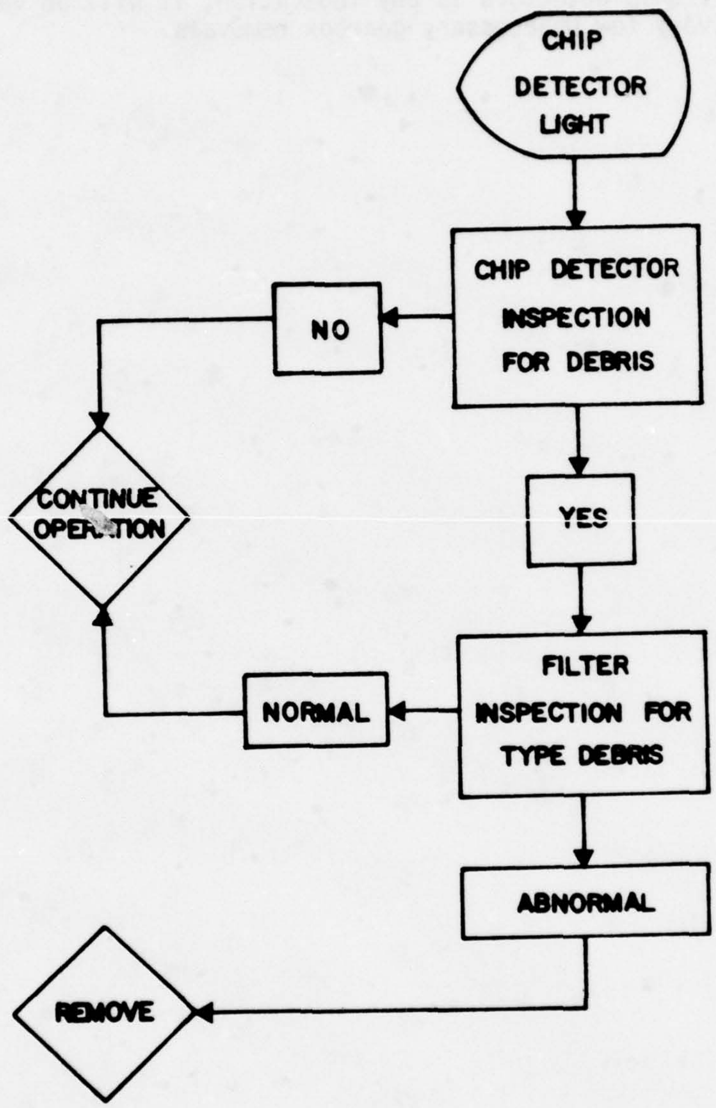


Figure 26. Recommended Gearbox Diagnostics System.

ADVANCED CONCEPTS

There are many advanced concepts that are being examined today for possible inclusion in the designs of future helicopter transmission systems. Some of these concepts are merely in the paper study stage, some have progressed to demonstration hardware, and some have reached the full-size hardware stage and have actually been tested on aircraft. In general, it is difficult to evaluate accurately the impact of these concepts on transmission reliability, since for the most part they are far from being fully developed. This chapter will, however, examine some of the newer concepts with respect to reliability and maintainability and will comment on their potential impact on the R&M characteristics of future drive trains.

ROLLER GEAR DRIVE

The roller gear drive is no longer a new concept. Unlike most of the other concepts which will be discussed here, full-size roller gear drives have been designed, fabricated, and tested such as that developed by Sikorsky for USAAMRDL, shown in Figure 27. The roller gear drive, as the name implies, is a combination roller and gear drive in an epicyclic arrangement. The rollers, which are integral with and located on either side of the gear members, have outside diameters coincident with the gear pitch diameters. In addition to providing support (in place of bearings) for the gear members, they contribute to the driving power as in a pure roller drive.

A half cross section view of the 19.85-to-1 reduction ratio roller gear drive, built and tested by Sikorsky Aircraft, is shown in Figure 27, while a top view illustrating the gear meshes is shown in Figure 28. Power is introduced to this unit by means of the internal spline of the sun gear. The power is transmitted from the sun gear to the first-row pinions by means of two geared surfaces located on either end of the sun and first-row pinions. Power is then transferred from the first to the second row of pinions by the centrally located geared surfaces of these components and finally to the ring gear from the second row of pinions. The second-row pinions are positioned by means of centrally located spherical bearings, which are used to react the torque through the roller gear unit. There are two especially interesting characteristics from a reliability point of view to note about the roller gear drive. First, the only bearings in the unit are those used to react the torque through the system. Both the sun gear and first-row pinions are supported entirely by the roller elements adjacent to the geared surfaces. From a reliability standpoint, fewer bearings, of course, mean greater reliability. The second aspect of the roller gear drive to note is the complexity of the roller gear elements, which is best illustrated by the exploded cross-sectional views of the first-row pinions of Figure 29. Because of the proximity of the various geared and roller surfaces to each other, it was impossible to make these components out of a single piece of metal. Thus, they were fabricated by electron-beam-welding the various elements together. These welds proved to be the most troublesome aspect of the roller gear drive program, and led to the redesign of

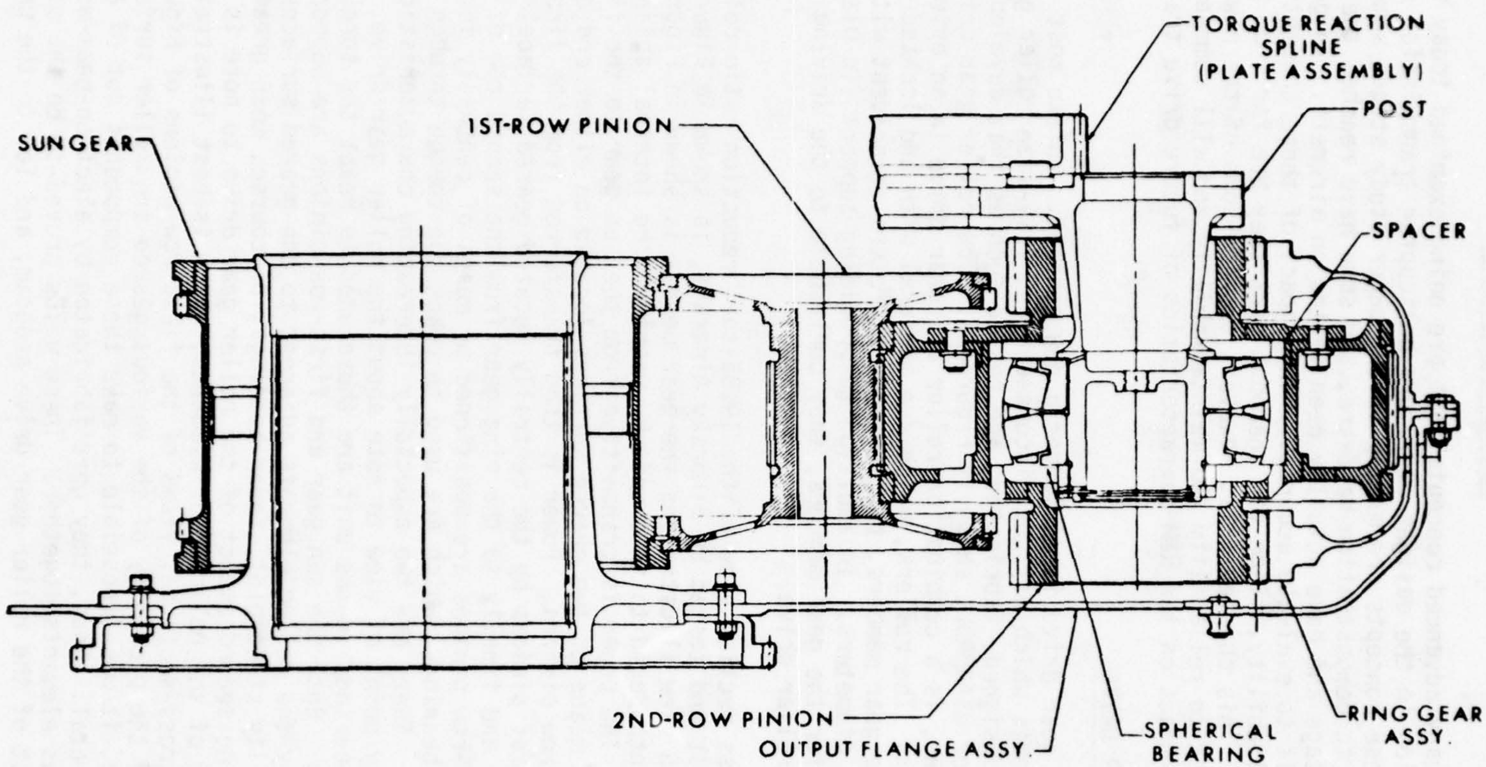


Figure 27. Cross Section of Sikorsky Roller Gear Drive.

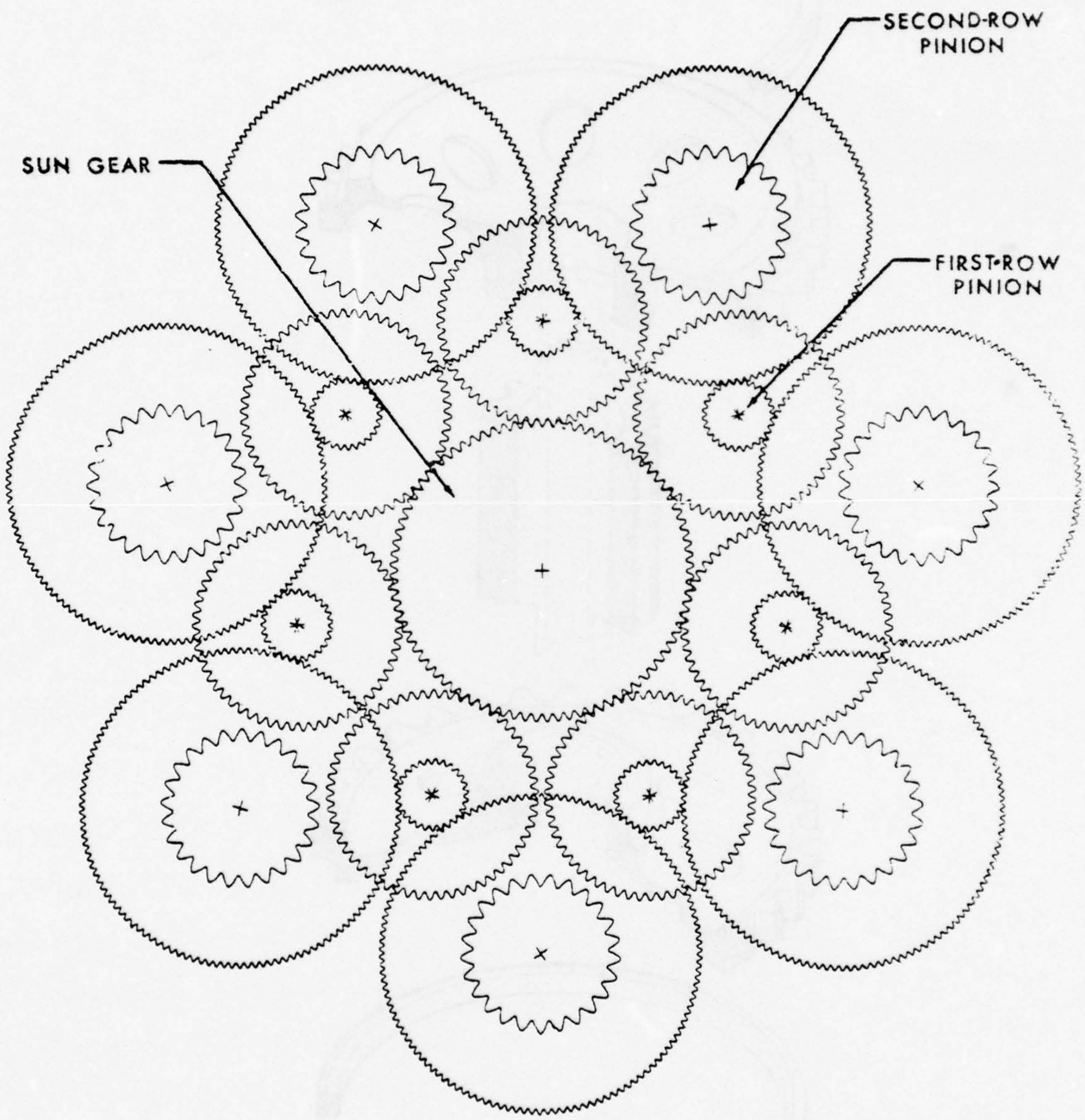


Figure 28. Roller Gear Drive - Gear Arrangement.

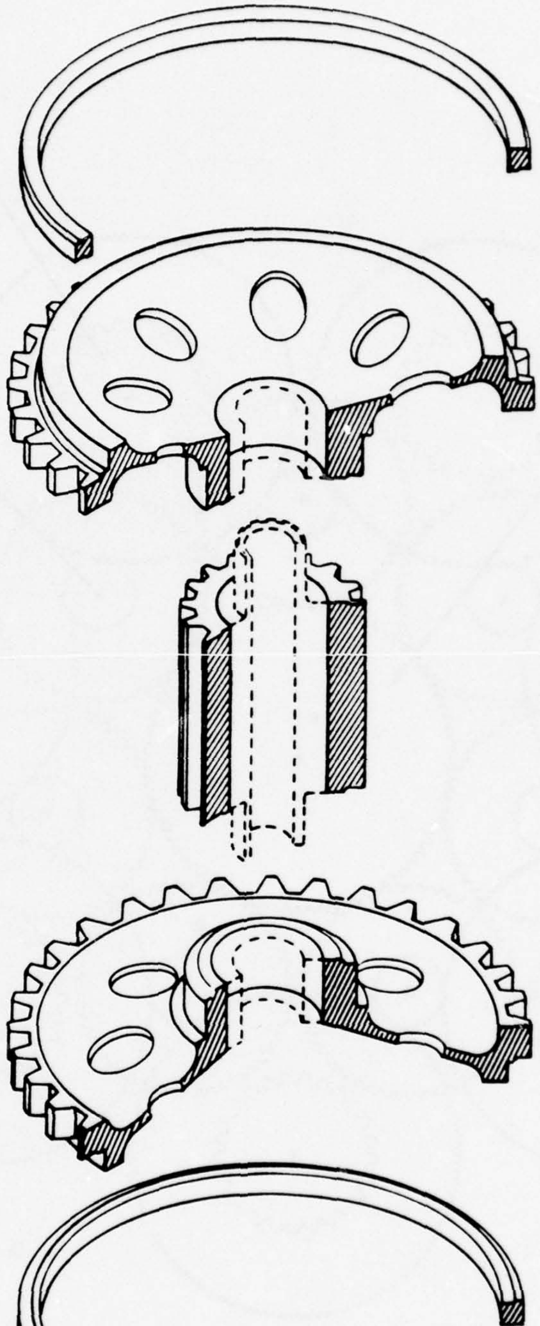


Figure 29. Exploded Cross Section - Roller Gear First-Row Pinion.

many of the components. Although improvements were made throughout the program in the design, execution, and inspection of these welds, at the conclusion of the program it could not be stated that the welds had shown sufficient integrity so as not to leave the structural reliability of the unit open to question.

The roller gear drive itself was proven to be a viable concept for helicopter transmission. Reduction ratios up to 100:1, which cannot be approached by conventional planetaries, may be attained with roller gear drives in flat compact packages that are well suited to today's helicopter transmissions. If the component fabrication problem could be solved, it is likely that roller gear drives could be advantageously employed in future transmissions and contribute greatly to increased drive system reliability.

FREE PLANET

The free planet, schematically shown in Figure 30, is another concept that offers high reduction ratios in a relatively compact package. Like the roller gear, the free planet utilizes compound gear elements to achieve the high reduction ratio. The free planet, however, unlike the roller gear drive, which is a star system (i.e., the pinions do not translate), is a true planetary where the pinions rotate about the sun gear. The free planet dispenses entirely with bearing support and reactions. The free planet is designed utilizing the "balance line" concept wherein the normal and tangential gear forces keep the pinions in equilibrium. Torque is reacted through a stationary ring gear while a rotating ring gear provides the output. The free planet concept has been successfully demonstrated by Curtiss-Wright Corporation by means of a 500 hp, 19.2425:1 reduction ratio unit. From a reliability standpoint, the free planet appears to offer substantial advantage over conventional planetaries, in that bearings, which are traditionally the most troublesome planetary components, are completely eliminated. The free planet, because of the compound nature of the pinions, may have the same type of fabrication problems as the roller gear drive. The demonstration hardware relied on piloted splines for the fabrication of the compound gear elements. Whether this would lead to an unacceptable weight penalty on flight hardware is questionable, although the complete elimination of bearings and the single pinion row may permit this type of fabrication in an acceptably light free planet unit. Perhaps a more serious problem with the free planet concept, however, is the fact that the free planet, in order to obtain a high reduction ratio, is much more elongated than conventional planetaries. Since the trend in recent transmissions is towards flatter, lower gearboxes, the free planet may be somewhat troublesome to conveniently fit into the envelope of future transmissions.

HIGH CONTACT RATIO GEARS

High contact ratio gearing, depicted in Figure 31, is another advanced concept that is not basically a new idea. This concept is essentially aimed at reducing the face width, and hence the weight, of spur gears by

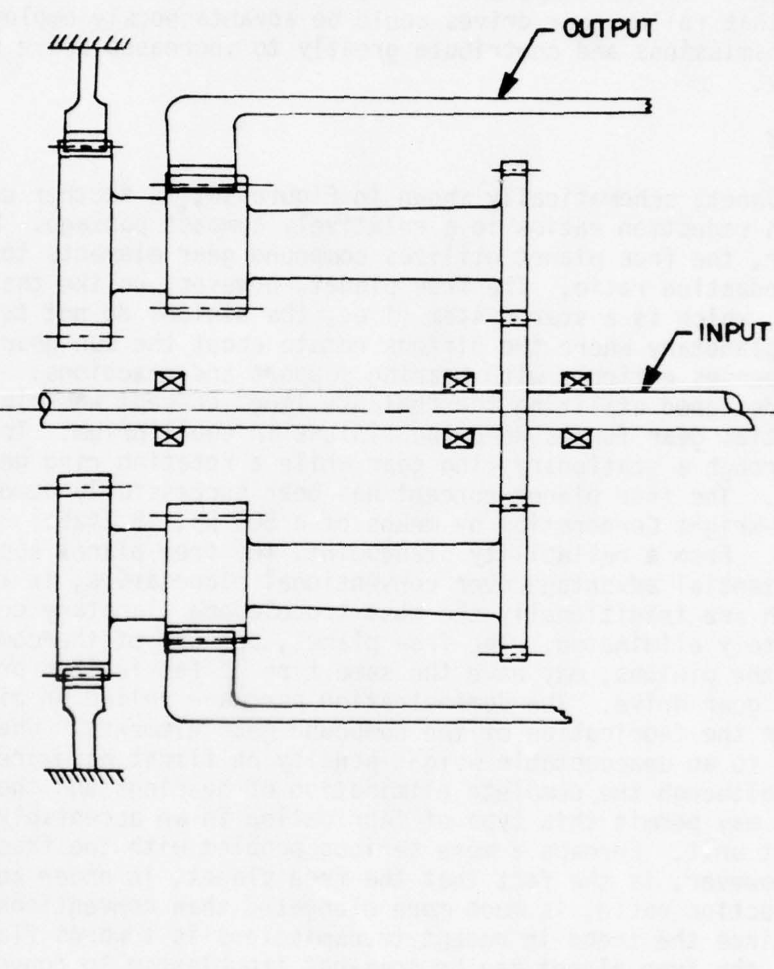


Figure 30. Free Planet Reduction Unit.

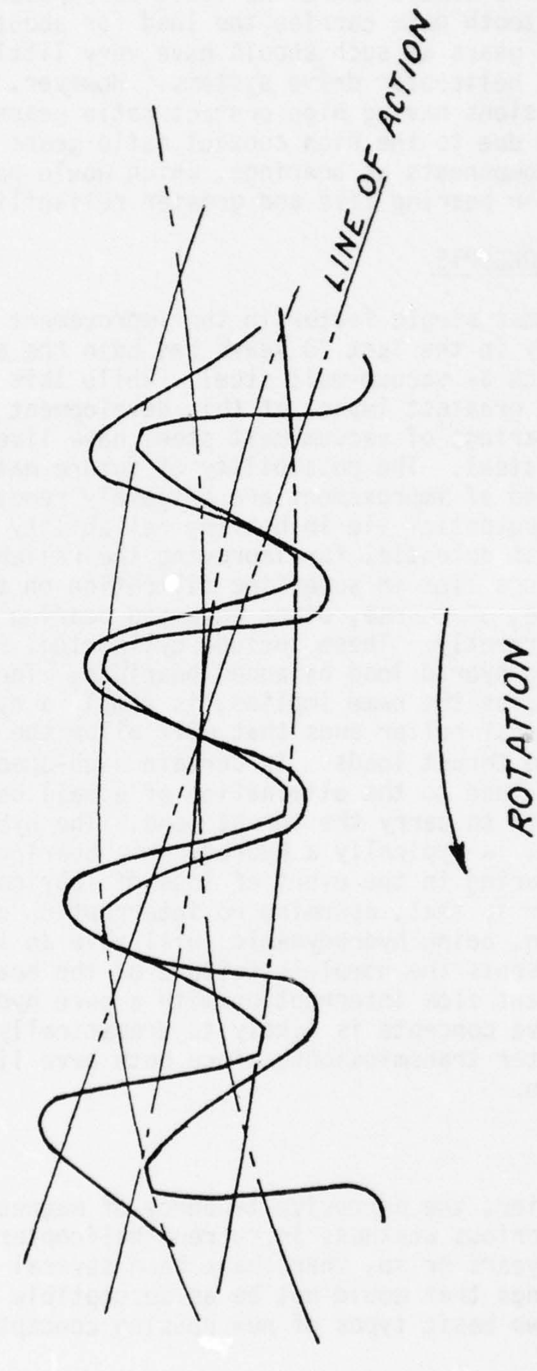


Figure 31. High Contact Ratio Gears.

means of increasing the number of teeth in a spur gear mesh that share the transmitted load. A high contact ratio gear set is designed so that at least two tooth pairs always share the load, as opposed to conventional designs where one tooth pair carries the load for about half of the time. High contact ratio gears as such should have very little direct effect on the reliability of helicopter drive systems. However, if the weight allocation to transmissions having high contact ratio gears is not changed, the weight savings due to the high contact ratio gears could be distributed among such components as bearings, which would permit the designer to design for higher bearing life and greater reliability.

ADVANCED BEARING CONCEPTS

Probably the greatest single factor in the improvement of helicopter transmission reliability in the last 20 years has been the advent of extremely clean materials such as vacuum-melt steel. While this effect has been felt in gears, the greatest impact of this development has been in the bearing field. Bearings of vacuum-melt steel have lives six to ten times those of air-melt steel. The possibility of future material developments leading to this kind of improvement are extremely remote. Where, then, does the greatest potential lie in bearing reliability improvement? Perhaps the greatest potential for improving the reliability of helicopter transmission bearings lies in superfine filtration on the order of 3 microns. There are, of course, other advanced bearing concepts that are being developed currently. These include cylindrical roller bearings with thrust capacity and hybrid load balanced bearings. The first concept, shown in Figure 32, as the name implies, is simply a cylindrical roller bearing with spherical roller ends that will allow the bearing to carry combined radial and thrust loads. In certain high-speed applications, this concept could lead to the elimination of a ball bearing that would normally be required to carry the thrust load. The hybrid load balanced bearing, Figure 33, is typically a hydrodynamic bearing with a backup rolling element bearing in the event of loss of lubrication. The advantage of this design is that, assuming no interruption of the lubricant supply, the bearing, being hydrodynamic, will have an infinite life. The roller bearing prevents the complete failure of the bearing, which normally occurs with lubricant flow interruption with a pure hydrodynamic bearing. Neither of the above concepts is likely to dramatically increase the reliability of helicopter transmissions, since both have limited applications in the transmission.

ADVANCED HOUSINGS

As was stated earlier, the corrosive tendency of magnesium housings is perhaps the most serious weakness in current helicopter transmissions. Within the past 5 years or so, there have been several attempts to develop new types of housings that would not be as susceptible to corrosion. Here we will consider two basic types of new housing concepts.

The first of these is the composite housing. Composite housings have certain very desirable advantages over magnesium housings. Corrosion is

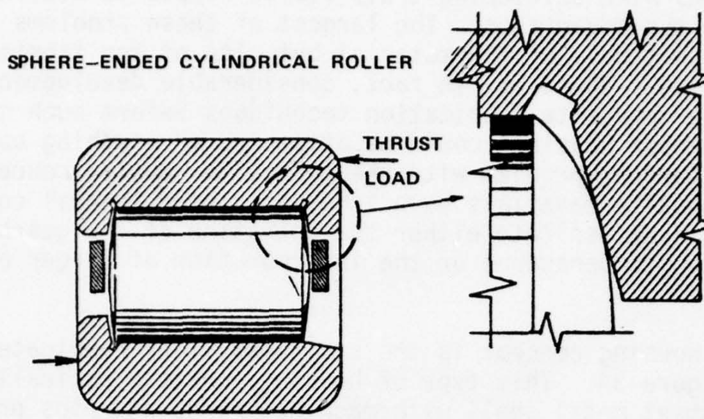


Figure 32. Cylindrical Roller Bearing With Thrust Capacity.

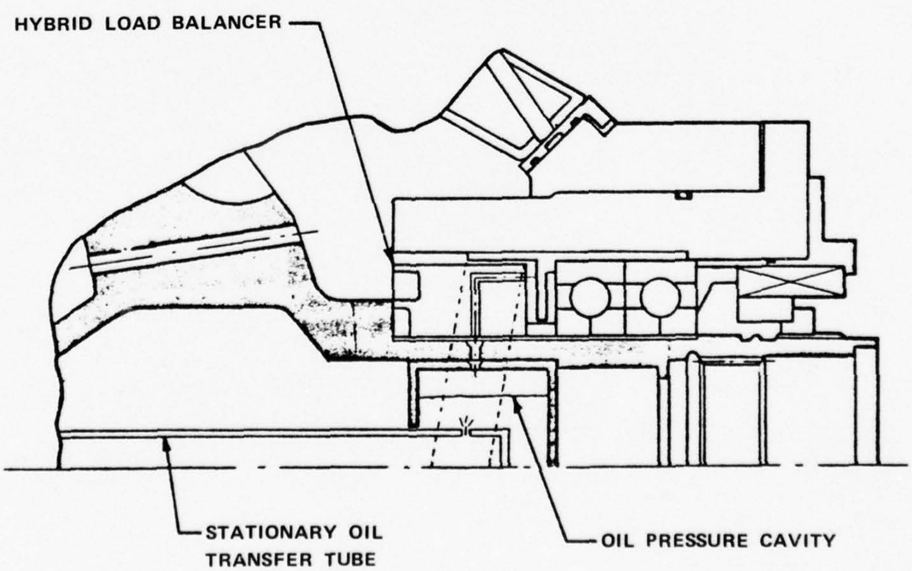


Figure 33. Hybrid Load Balanced Bearing.

for all intents and purposes eliminated as a problem. Composite housings are lighter than magnesium and because of the unique properties of new composite materials are considerably more ballistic tolerant. Unfortunately, the problems with developing truly viable composite housings are even greater than the advantages. The largest of these problems is the prohibitive cost, not only of the material but also of the fabrication of this type of housing. There is, in fact, considerable development yet to be accomplished in composite fabrication techniques before such complex shapes as main gearbox housings could be attempted on anything but a prototype basis. A further problem with the composite housing concept is the fact that the composite materials have inherently poor thermal conductivity, which would necessitate either the operation of the gearbox at considerably higher temperatures or the incorporation of larger oil coolers.

Another advanced housing concept is the stainless steel fabricated housing, illustrated in Figure 34. This type of housing consists basically of a stainless steel sheet metal shell with machined rings and ribs providing the necessary mounting points and load paths. Welding is used to join the various elements. Studies have shown this type of housing to be considerably lighter than the standard magnesium housing while offering the obvious advantages that stainless steel has over magnesium. There may, however, be acoustic problems in using sheet metal for a gearbox housing. Fabrication problems, however, appear to be the major obstacles that must be overcome before the fabricated stainless steel housing is a truly competitive housing candidate.

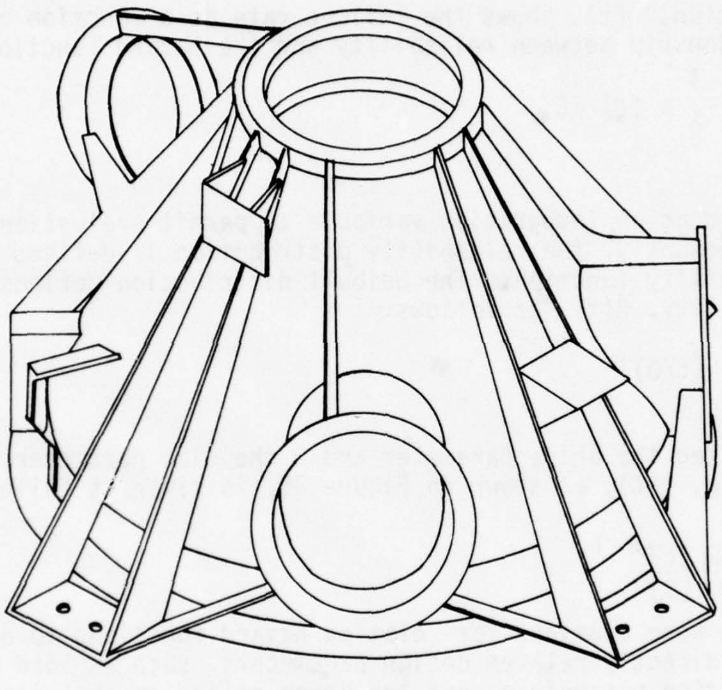


Figure 34. Stainless Steel Fabricated Housing.

RELIABILITY ESTIMATION TECHNIQUES

Two general methods were explored for estimating the reliability, R(t), for individual failure modes encountered in helicopter drive systems. The two methods considered, hazard function analysis and probabilistic design, each have their advantages and limitations. Unlike many reliability analyses where a constant failure rate and exponential distribution* is automatically assumed, the proposed techniques only make this assumption when it is applicable.

HAZARD FUNCTION ANALYSIS

A hazard function, h(t), shows the failure rate as a function of time. The general relationship between reliability and the hazard function is

$$R(t) = e^{-\int_0^t h(\xi)\, d\xi} \tag{1}$$

where ξ is used as an integration variable to permit evaluation of the integral. Frequently, the reliability distribution is defined by the Weibull reliability function. The Weibull distribution defines the cumulative reliability, R(t), as follows:

$$R(t) = e^{-(t/\theta)^{\beta}} \tag{2}$$

where β is called the shape parameter and θ the size parameter. The hazard function, h(t), as shown in Figure 35, is given as follows:

$$h(t) = \left[\frac{\beta}{\theta}\right]\left[\frac{t}{\theta}\right]^{\beta-1} \tag{3}$$

Two approaches were examined for relating hazard functions to drive system designs. One directly relates design parameters, such as load and speed, to hazard function parameters, and the other relies on empirical data from past designs. The first approach uses reliability distribution models that are pertinent to a specific failure mode and mechanism. Then an analytical relationship such as the Lundberg-Palmgren Theory for ball and roller bearings,[2,3] is postulated. Finally, the statistical variability

---

*The exponential distribution defines reliability as

$$R(t) = e^{-t/MTBF} \quad \text{or} \quad R(t) = e^{-\lambda t}$$

where

t = flight duration

λ = average failure rate for a particular category

[3]Lundberg, G., and Palmgren, A., DYNAMIC CAPACITY OF ROLLER BEARINGS, Royal Swedish Academy of Engineering Sciences, Stockholm, 1952.

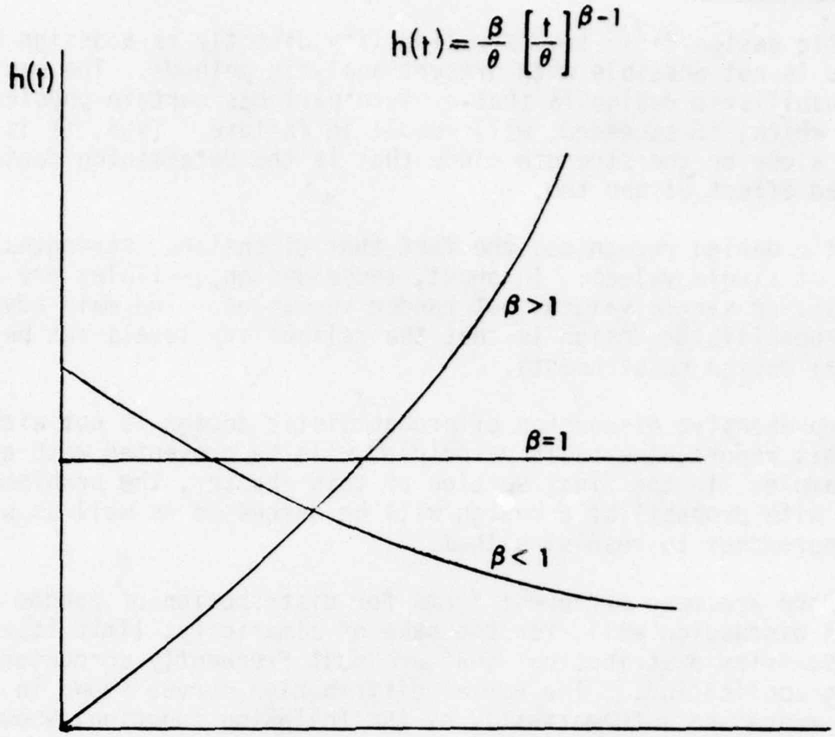


Figure 35. Hazard Function.

associated with the analytical model is evaluated to determine reliability. Similar models exist for gear teeth, such as those for spur gears.[4]

The second approach estimates drive system failure mode hazard functions based on historical experience of previous helicopter drive systems. This approach is based upon the reliability distribution defined by the Weibull reliability function. It establishes a size parameter and shape parameter for each part failure mode based on the methodology defined in Reference 5.

---

[4] Coy, J. J., Townsend, D. P., and Zaretsky, E. V., ANALYSIS OF DYNAMIC CAPABILITY OF LOW-CONTACT-RATIO SPUR GEARS USING LUNDBERG-PALMGREN THEORY, NASA Technical Note D-8029, Lewis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Lewis Research Center, Cleveland, Ohio, August 1975.

[5] Trustee, B., HELICOPTER DRIVE SYSTEM ON-CONDITION MAINTENANCE CAPABILITY, Sikorsky Aircraft Division, United Technologies Corporation; USAAMRDL Technical Report 75-57, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, July 1976, AD A028414.

PROBABILISTIC DESIGN

Probabilistic design [6,7,8] treats reliability directly as a design requirement. This is not possible with present analytic methods. The basic idea behind probabilistic design is that a given part has certain physical properties which, if exceeded, will result in failure. Thus, it is not the stress alone or the strength alone that is the determining factor, but the combined effect of the two.

Probabilistic design recognizes the fact that dimensions, strengths, stress, etc., are not single values. In short, these design variables are not deterministic or single valued, but random variables. The main advantage to using probabilistic design is that the reliability levels can be used as numerical design requirements.

While a comprehensive discussion of probabilistic design is not within the scope of this report, the basic principles will be presented with an illustrative example. In the final section of this chapter, the problems associated with probabilistic design will be discussed as well as some possible approaches to resolving them.

Although there are many different forms for distribution of random variables, this discussion will, for the sake of simplicity, limit itself to normal or Gaussian distribution, that are most frequently encountered in engineering applications. The normal distribution curve, shown in Figure 36, may be expressed mathematically by the following function, known as a probability density function (PDF):

$$f(x) = \frac{1}{\sigma_x \sqrt{2\pi}} e^{-\frac{(x-\mu_x)^2}{2\sigma_x^2}} \tag{4}$$

where

x = a random variable
μ_x = mean value of x
σ_x = standard deviation of x

A probability density function represents the distribution of values of a

---

[6] Haugen, E. B., PROBABILISTIC APPROACHES TO DESIGN, New York, John Wiley and Sons, Inc., 1968.

[7] Lipson, C., et al., RELIABILITY PREDICTION - MECHANICAL STRESS/STRENGTH INTERFERENCE, RADC Technical Report 66-710, Rome Air Development Center, Griffith AFB, New York, March 1967.

[8] Lipson, C., et al., RELIABILITY PREDICTION - MECHANICAL STRESS/STRENGTH INTERFERENCE (NONFERROUS), RADC Technical Report 68-403, Rome Air Development Center, Griffith AFB, New York, February 1969.

random variable. As can be seen from Equation (4), two quantities are necessary to describe the PDF of a random variable x: the mean (μ_X) and the standard deviation (σ_X). The mean value is defined as the centroid of the area under the PDF and is found from the following equation:

$$\mu_X = \int_{-\infty}^{+\infty} x f(x) dx \tag{5}$$

The standard deviation is obtained from a quantity known as the variance. Variance ($\sigma_X{}^2$) is a measure of the spread or dispersion of the PDF. The higher the variance, the greater the spread between high and low values of the random variable. Variance is found from the following equation:

$$\sigma_X{}^2 = \int_{-\infty}^{+\infty} (x - \mu_X)^2 f(x) dx \tag{6}$$

Variance can be interpreted as the moment of inertia of an area of the PDF about the mean, or centroid. Standard deviation, which is a more convenient quantity than variance since it has the same units as x and μ_X, is simply the square root of the variance.

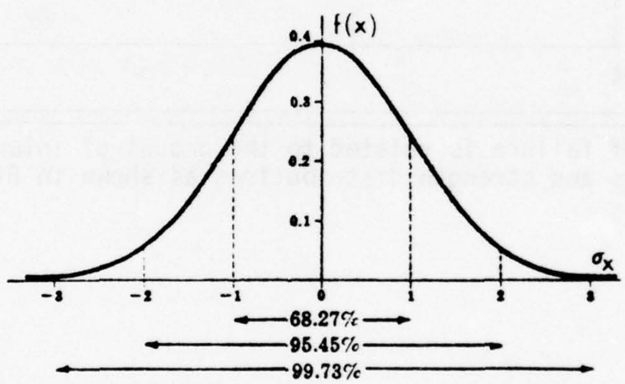


Figure 36. Normal Distribution PDF.

The algebra of random variables is somewhat different from the algebra of real numbers since, unlike real numbers where only one number is needed to describe a variable, we now have two numbers that describe the variable: its mean and standard deviation. The derivation of the various algebraic operations is accomplished by what is known as moment-generating functions. The derivations of the algebraic functions will not be presented here. The reader is referred to Reference 6 should he wish more detail. Table 4 shows the basic algebraic functions of random variables. As can be seen, the operations are considerably more complex than those of real numbers and are not intuitively obvious to those unaccustomed to dealing with random variables.

TABLE 4. MEAN AND STANDARD DEVIATIONS FOR FUNCTIONS OF INDEPENDENT RANDOM VARIABLES x AND y.

Function*	Mean	Standard Deviation
$z = a$	a	0
$z = ax$	$a\mu_x$	$a\sigma_x$
$z = x + a$	$\mu_x + a$	σ_x
$z = x \pm y$	$\mu_x \pm \mu_y$	$(\sigma_x^2 + \sigma_y^2)^{1/2}$
$z = xy$	$\mu_x \mu_x$	$(\mu_x^2 \sigma_y^2 + \mu_y^2 \sigma_x^2 + \sigma_x^2 \sigma_y^2)^{1/2}$
$z = x/y$	μ_x/μ_y	$\frac{1}{\mu_y^2}\left[\frac{\mu_x^2 \ \sigma_y^2 + \mu_y^2 \ \sigma_x^2}{\mu_y^2 + \sigma_y^2}\right]^{1/2}$
$z = x^2$	$\mu_x^2 + \sigma_x^2$	$(4\mu_x^2 \sigma_x^2 + 2\sigma_x^4)^{1/2}$

* a = constant

The probability of failure is related to the amount of interference between the stress and strength distributions as shown in Figure 37.

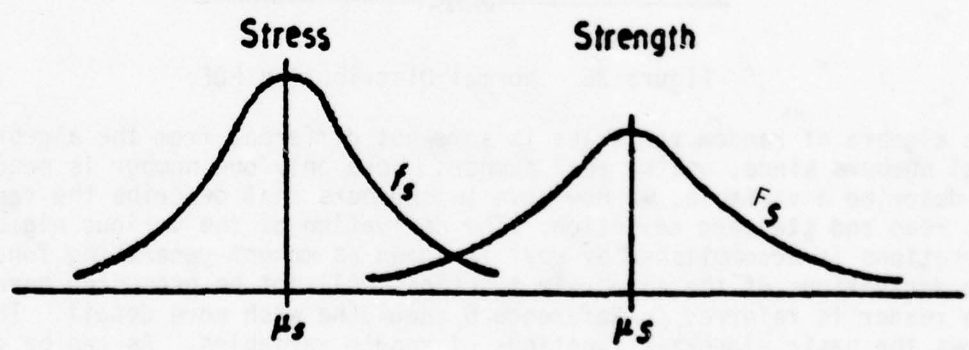


Figure 37. Stress-Strength Interaction Diagram.

For normal distribution, this can be expressed as follows:

$$Z = \frac{F - f}{(\sigma_F{}^2 + \sigma_f{}^2)^{\frac{1}{2}}} \quad (7)$$

where

F = mean strength
f = mean stress
σ_F = standard deviation of strength
σ_f = standard deviation of stress

Values for the function Z for various levels of reliability are given in Table 5.

TABLE 5. PROBABILITY OF FAILURES (P_f) AND FUNCTION Z.

P_f	Z
.01	2.326
.001	3.090
.0001	3.719
.00001	4.265
.000001	4.753
.0000001	5.199
.00000001	5.610
.000000001	5.997
.0000000001	6.361
.00000000001	6.700

Apart from its uniformity of approach, probabilistic design has several desirable features. Unlike current deterministic methods, it introduces the notion of component failure into current design procedures where it was thought not to have existed before. It directly links reliability to design variables. It allows the design engineer to compare two designs to see which is better, even if absolute reliability levels cannot be computed. The most attractive feature of probabilistic design is its potential for more efficient utilization of weight. Reference 9 has shown that setting reliability goals for components can lead to smaller components, such as a drive shaft, which are lighter than if they were designed to deterministic methods.

Perhaps the best way to continue this discussion of probabilistic design is to present an example using both conventional and probabilistic analysis. The example used is a simple cylindrical rod. First, the

[9] Kecocioglu, D. B., and Vincent, R. L., RELIABILITY APPROACH TO ROTATING-COMPONENT DESIGN, NASA Technical Note D-7846, National Aeronautics and Space Administration, Washington, D. C., February 1975.

problem will be solved using conventional analytical techniques. Then the same example will be solved using probabilistic techniques. By contrasting the two examples, the main features of probabilistic design can be illustrated.

Conventional Analysis

Find the required diameter of a 125,000 psi heat treat 4340 steel rod that must support a static ultimate tensile load of 5000 pounds, using a factor of safety of 1.5.

$$f_t = \frac{F_{tu}}{F.S.} \tag{8}$$

$$f_t = \frac{P}{A} \tag{9}$$

$$A = \frac{\pi}{4} d^2 \tag{10}$$

where

f_t = tensile stress (psi)
P = load (lb)
A = area (in^2)
F_{tu} = ultimate stress (psi)
F.S. = factor of safety
d = diameter (in.)

By substitution, we have

$$d^2 = \frac{4P(F.S.)}{\pi F_{tu}} \tag{11}$$

where

P = 5000 lb
F.S. = 1.5
F_{tu} = 125,000 psi

and

$$d = \frac{(4)(5000)(1.5)}{\pi(125,000)}^{1/2} = .2764 \text{ in.} \tag{12}$$

This solution will be the minimum diameter. Therefore, the diameter on the drawing will be .287 ± .010 inch.

Probabilistic Analysis

Find the required diameter of a 125,000 psi heat treat 4340 steel rod that must support a static ultimate tensile load of 5000 pounds with a probability of failure of not more than .000001, i.e., one failure per million parts. The ultimate strength of the material has a standard deviation of 7000 psi, the load 200 pounds, and the diameter .0033 inch (based on a diameter tolerance of ±.010 inch).

$$f_t = \frac{P}{A} \tag{13}$$

$$A = \frac{\pi}{4} d^2 \tag{14}$$

$$\sigma_A = \frac{\pi}{4} \left[4\bar{d}^2 \quad \sigma d^2 + 2\sigma_d{}^4\right]^{\frac{1}{2}} \tag{15}$$

$$\sigma_{f_t} = \frac{1}{A} \left[\frac{P^2 \ \sigma A^2 + A^2 \sigma P^2}{A^2 + \sigma_A{}^2}\right]^{\frac{1}{2}} \tag{16}$$

$$Z = \frac{F_{tu} - f_t}{\left[\sigma^2_{F_{tu}} + \sigma^2_{f_t}\right]^{\frac{1}{2}}} \tag{17}$$

where

f_t = tensile stress (psi)
P = load (lb)
A = area (in.^{2})
F_{tu} = ultimate stress (psi)
d = diameter (in.)
Z = function based on P_f (Table 5)

Values for the mean and standard deviation are based on the equations given in Table 4. Equations (15) and (16) represent the standard deviation for area and stress since, algebraically

$A = \frac{\pi}{4} d^2$ and $f_t = P/A$ are equivalent to $Z = ax^2$ and

$Z = x/y$ respectively. Summarizing we have, for stress

$$f_t = (f_t, \sigma_{f_t}) \text{ psi}$$

$$P = (P, \sigma_p) = (5000, 200) \text{ psi}$$

$$A = (A, \sigma_A) \text{ in.}^2$$

$$d = (d, \sigma_d) = (d, .0033) \text{ in.}$$

For strength

$$F_{tu} = (\bar{F}_{tu}, \sigma_{F_{tu}}) = (125{,}000,\ 7000)\ \text{psi}$$

For stress/strength

$$Z = 4.7534 \text{ for a } P_F \text{ of } .000001$$

Calculations:

$$A = \frac{\pi}{4} d^2 = .7854d^2 \qquad \text{(Ref. Equation (14))}$$

$$\sigma_A = \frac{\pi}{4}\left[4d^2(.0033)^2 + 2(.0033)^4\right]^{\frac{1}{2}} = .0052d \qquad \text{(Ref. Equation (15))}$$

$$f_t = \frac{P}{A} = \frac{5000}{.7854d^2} = \frac{6366}{d^2} \qquad \text{(Ref. Equation (13))}$$

$$\sigma_{f_t} = \frac{1}{.7854d^2}\left[\frac{(5000)^2(.0052d)^2 + (.7854d^2)^2(200)^2}{(.7854d^2)^2 + (.0052d)^2}\right]^{\frac{1}{2}}$$

(Ref. Equation (16))

$$\approx \frac{1}{.6169d^3}\ (676 + 24674d^2)^{\frac{1}{2}}$$

$$Z = 4.7534 = \frac{125{,}000 - \dfrac{6366}{d^2}}{\left[7000^2 + \dfrac{1}{.3806d^6}(676 + 24674d^2)\right]^{\frac{1}{2}}}$$

(Ref. Equation (17))

Using iterative numerical methods, the above equation yields a mean shaft diameter of .2712 inch.

Note from the two examples, the differences between the conventional deterministic and the probabilistic solutions. First, with the probabilistic example, reliability is a numerical design requirement; this is not the case with the deterministic method. In addition, note that more information is required for the probabilistic solution. Both mean and standard deviations of all quantities must be known. Also note that the probabilistic solution is considerably more difficult than the deterministic solution. The probabilistic example required an iterative solution even for this simple case.

The above differences illustrate both the advantages and disadvantages of probabilistic design. As was stated earlier, with probabilistic design, reliability is an explicit quantitative consideration, not a vague implicit consideration. Furthermore, by being able to quantify reliability, the design solution becomes more meaningful; it is certainly more significant to state that a part has a probability of failure of one in one million than to state that it has a factor of safety of 1.5. This also facilitates design trade-offs between weight and reliability. Unfortunately, the obstacles to the incorporation of probabilistic design in the aerospace industry are substantial. One of the most serious technical barriers to adoption of probabilistic design is the lack of an adequate data base. The availability of strength distribution data for engineering materials is by no means sufficient at present to allow the extensive use of probabilistic design. A second problem is that, as was seen in an earlier chapter, current engineering methods are on the whole not very accurate in determining strength. While the use of margins and factors of safety is used to account for the variations in material strength that probabilistic design considers, it is also used to account for inaccuracies in the analytical modes, which probabilistic design does not consider. This problem may of course be skirted by designing for higher reliabilities where the analytical model is questionable, but a careful evaluation of current analytical techniques with respect to their accuracy should be accomplished before probabilistic design is seriously undertaken. There are other, perhaps not as serious, but nonetheless very real problems to consider. First, the complexity of a probabilistic design system would necessitate computerization to a far greater extent than is currently the rule. Second, since few design engineers have been exposed to random variables, a substantial amount of retraining would be necessary. There are other problems too. Both FAA and military regulations require factors or margins of safety for certain flight-critical components. Since margins and factors of safety have no meaning in probabilistic design, changes in such regulations would have to be made.

Another problem with probabilistic design is its lack of administrability. For example, if a part fails during test, it would be impossible to know if it was a real design deficiency or simply the one failure in one million that the part was designed for.

Although there are many problems with probabilistic design, there is no denying its basic appeal in bringing reliability directly into the design process, given the increasing importance of reliability to both the helicopter operator and manufacturer. Labor costs, even those of the military, are increasing at an accelerated rate, which means there is a premium on reliable aircraft that require less maintenance. To the manufacturer, reliability is becoming increasingly important, since he is being asked to guarantee the reliability of his product. With lower than predicted reliability levels, the manufacturer could quickly see his profit margin evaporate. There are some like Haugen[10] who believe that probabilistic

---

[10] Haugen, E. B., and Wirsching, P. H., PROBABILISTIC DESIGN, Machine Design, 15 April-12 June 1975.

design is inevitable; there are others who believe that such statistical design techniques are impractical. This study merely recommends that it be investigated further because of the crucial importance of reliability.

ARMY FACILITIES

During the course of this program, visits were made to the overhaul facility at Corpus Christi Army Depot (CCAD), Texas, and to Army operational facilities at Fort Rucker, Alabama, and Fort Campbell, Kentucky. The purpose of these visits was to learn first hand the problems experienced in maintaining and overhauling the drive systems of aircraft currently in the Army inventory. The following are the main findings of these visits.

HOUSING CORROSION

Overhaul personnel at Corpus Christi cited housing corrosion as by far the most common discrepancy observed in gearboxes sent back for overhaul. According to overhaul personnel, some corrosion is seen on virtually all housings. Although the corrosion usually occurs around studs and housing interfaces, severe corrosion on the outside surfaces of the housings is not unusual and about 70 percent exhibit corrosion inside the gearbox. Organizational maintenance personnel at Fort Rucker and Fort Campbell, on the other hand, stated that corrosion of housings was extremely rare. While it is true that the organizational maintenance personnel would not be able to detect interface or interior corrosion, there still seemed to be a large disparity in the significance of corrosion at the two levels of maintenance. It seems that the reason for this disparity lies with the inadequacy of the shipping containers in keeping moisture out. This theory is supported by the fact that the dessicant used to absorb moisture in the containers was often found saturated when the containers were opened at Corpus Christi.

ACCESSIBILITY

The most common complaint of organizational maintenance personnel was the lack of accessibility to the drive train components that required frequent servicing. Replacement of the oil filter on the UH-1, for example, requires the repairman to be part contortionist because of obstructions by the airframe and other systems. Certain drive shaft sections on the CH-47 required the removal of an adjacent section before the removal of the desired section could be effected. There were many other such design deficiencies that were delineated by the organizational maintenance personnel, and these deficiencies point up the need to pay careful attention to accessibility during aircraft design.

FIELD PROBLEMS

The tail rotor drive shaft system is generally the most common field repair item in the drive system. Each aircraft seems to have a particular component that is the most troublesome. With the UH-1/AH-1, the diaphragm coupling is by far the most troublesome although the hanger bearings also frequently cause problems. Because it is exposed, the OH-58 tail drive shaft system is particularly bad with respect to reliability. The hanger bearings are a constant maintenance problem, and because of very low damage tolerance, the entire OH-58 shaft is also a frequent replacement item. There is much less trouble with the CH-47 synchronizing shaft, because the shaft is well protected, the bearings are lubricated through grease fittings every 25 hours, and the damper design is superior to that of other aircraft.

Seal leakage is the most common problem associated with the gearboxes themselves. Again, the UH-1/AH-1 drive system is the biggest offender. Although the CH-47 has no especially serious seal leakage problem, the input shafts of the combining gearbox consistently fling the grease from the spline because there is no seal there at all.

It was noted that the tooling required to perform field maintenance is for the most part unnecessarily complicated and heavy. This is especially true of the CH-47 where the tools for organizational maintenance personnel weigh literally hundreds of pounds.

OVERHAUL PROBLEMS

Overhaul personnel brought out the fact that it is terribly expensive and time consuming to completely strip magnesium housings of their protective coatings prior to inspection and then have to reapply the coatings before the housings are returned to service. It is their contention that the housings can be safely magnaflux inspected with the coatings left on. In other words, if there is a crack in the housing, there will be a crack in the paint also. In areas that are repainted in the field, the paint may be stripped locally or eddy current methods may be used for inspection.

Several Corpus Christi personnel brought out the fact that expensive and hard-to-get parts often are scrapped with small defects because either insufficient material was left for rework or no rework procedure was provided. This leads not only to high maintenance costs, but also to supply problems because of the long lead times to acquire the components involved. During design, however, it is difficult to make material allowances for rework due to weight requirements. In a related conversation, CCAD personnel indicated that integral shaft/bearing races were not cost effective from an overhaul standpoint. Here the spalling of a bearing would mean the scrappage of expensive gears having long resupply lead times.

CCAD has an extensive bearing inspection and rework facility including a clean room and some very sophisticated inspection equipment. Used bearings are 100 percent inspected for defects, while new bearings in critical applications, i.e., primary power train, are also 100 percent inspected. CCAD personnel noted that corrosion is the primary reason for rejecting new bearings. Bearing quality also seems to be falling off lately and rejection of new bearings for other than corrosion is becoming more common.

CONCLUSIONS

1. There are two distinct methods that can be used to predict reliability during the design stage: hazard function analysis, based on historical data, and probabilistic design. Each has advantages and disadvantages as described below.

   Although at present the available helicopter drive system R/M does not allow correlation of hazard function parameters to such design parameters as stress, hazard functions can be a very useful tool in the design of helicopter transmissions. A hazard function analysis performed early in the design stage can provide the design engineer with upper and lower bounds of the MTBF, thus providing an indication of the adequacy of the design with respect to the design goal. The hazard function analysis can also show the designer the areas where design changes will have the greatest impact in improving the MTBF. Considerably more effort is needed before hazard function parameters can be directly related to design parameters. This effort must come not only in improving the quantity and quality of gearbox experience data, but also in developing more refined design analytical techniques.

   Probabilistic design offers a distinct advantage over the presently used deterministic design system in that reliability may be treated directly as a numerical design requirement. In addition, probabilistic design permits quantitative tradeoffs between weight and reliability. A considerable effort is required, however, before the institution of a purely probabilistic approach to design.

2. The significant reliability improvement in helicopter drive systems over the past 10 to 15 years has been due primarily to the development of extremely "clean" gear and bearing materials such as consumable electrode vacuum-melt and vacuum-degassed steels. It appears unlikely, however, that material advances in the next 10 to 15 years will have as dramtic an effect.

3. With the advent of on-condition maintenance gearboxes, it is probable that gearbox removals caused by age-dependent failure modes will become more prevalent. Among these will be such problems as excessive wear, particularly of overrunning clutch components, and housing corrosion.

4. Diagnostic techniques such as SOAP, vibration analysis, and AIDAPS do not yet appear to be cost-effective candidates for extensive application to helicopter gearboxes.

5. There are two approaches for dealing with reliability growth of helicopter drive systems. The two approaches considered, a generalized test plan and a UTTAS type test plan, each have advantages and limitations.

- <u>Generalized Test Plan</u> - Design requirements have been determined from reliability demonstration requirements. Test programs are designed to consider the type and distribution of failure modes experienced in previous designs.

  The method may be insensitive to new design techniques or constrained by particular program considerations.

- <u>UTTAS Test Plan</u> - The test plan implemented by the UTTAS program has been highly successful. It is applicable to programs with the same design constraints, comparable design technologies, and similar failure distributions.

Regardless of the approach to reliability development, reliability demonstrations are more economically performed during early production field experience than during development testing because costs are spread over more units, a better evaluation of the service environment can be performed, and a broader statistical base exists.

6. Three methods considered for designing to maintainability requirements of helicopter drive systems are time line analysis, historical task element, and qualitative maintainability. Each have their advantages and limitations.

- <u>Time Line Analysis</u> - Allows accurate estimation of manhours for representative repairs. It relates the details associated with a particular repair to the predicted task time. The analysis for depot repairs considers primary failures, secondary failures, and nonfailures repaired due to part degradation. The method relies on the judgment of the analysis and is time consuming for depot repairs of the main transmission due to the large number of different tasks that have to be estimated.

- <u>Historical Task Element</u> - Permits a rapid assessment of the design, provides limits for the maintenance manhours of each task, and provides sensitivity to some general installation features. The method relies on empirical data from past designs and may be insensitive to new design techniques. No data appears to be currently available for depot repairs.

- <u>Qualitative Maintainability</u> - A qualitative approach allows the factors that influence maintainability characteristics to be considered readily during design. R&M personnel should review with design engineers the maintainability aspects of gearbox design as early as possible in the design process.

RECOMMENDATIONS

1. Probabilistic design, because of its basic appeal in bringing reliability requirements directly into the design analysis, should be further investigated for possible future use in the design of helicopter drive systems. The first step should be a feasibility study that examines the advantages, disadvantages, and problems or probabilistic design as well as develops a strategy for overcoming these problems. More effort should also be expanded on the development of hazard functions as a reliability prediction technique. The thrust of this effort should be in improving the quality and quantity of the data gathered at depot maintenance activities.

2. Superfine oil filters (under 10 micron absolute) and noncorroding housings appear to be the developments that offer the best potential for substantially improving helicopter drive system reliability. Hence, it is recommended that the development of these concepts be actively pursued.

3. An engineering analysis should be performed on all components that are returned to depot. The analysis should contain a detailed engineering failure analysis and relevant maintenance data.

4. An inventory of the flight times on individual aircraft should be maintained to track the time on individual drive components still in service and to permit a proper accounting of total time on components that have not failed. Flight-line data should be sampled by each aircraft manufacturer. The data should be monitored, tracked, and significant problems noted. Engineers should regularly visit overhaul facilities to gain first-hand knowledge of transmission conditions after field experience.

5. Fuzz burn-off chip detection in conjunction with filter inspection appears to be the most cost-effective diagnostic system for use in helicopter transmissions. Spectrometric oil analysis (SOAP) and particle count techniques will be rendered ineffective by the advent of superfine filters; hence, further research into these areas is not recommended. It is <u>not</u> recommended that the development of vibration analysis techniques be actively pursued, since it is unlikely that such a diagnostic system could be cost effective.

REFERENCES

1. Bowen, C. W., et al., MODE OF FAILURE INVESTIGATIONS OF HELICOPTER TRANSMISSIONS, Bell Helicopter Company; USAAVLABS Technical Report 70-66, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1971, AD 881610.

2. Lundberg, G., and Palmgren, A., DYNAMIC CAPACITY OF ROLLING BEARINGS, Royal Swedish Academy of Engineering Sciences, Stockholm, 1947.

3. Lundberg, G., and Palmgren, A., DYNAMIC CAPACITY OF ROLLER BEARINGS, Royal Swedish Academy of Engineering Sciences, Stockholm, 1952.

4. Coy, J. J., Townsend, D. P., and Zaretsky, E. V., ANALYSIS OF DYNAMIC CAPABILITY OF LOW-CONTACT-RATIO SPUR GEARS USING LUNDBERG-PALMGREN THEORY, NASA Technical Note D-8029, Lewis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Lewis Research Center Cleveland, Ohio, August 1975.

5. Trustee, B., HELICOPTER DRIVE SYSTEM ON-CONDITION MAINTENANCE CAPABILITY, Sikorsky Aircraft Division, United Technologies Corporation; USAAMRDL Technical Report 75-57, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, July 1976, AD A028414.

6. Haugen, E. B., PROBABILISTIC APPROACHES TO DESIGN, New York, John Wiley and Sons, Inc., 1968.

7. Lipson, C., et al., RELIABILITY PREDICTION - MECHANICAL STRESS/STRENGTH INTERFERENCE, RADC Technical Report 66-710, Rome Air Development Center, Griffiss AFB, New York, March 1967.

8. Lipson, C., et al., RELIABILITY PREDICTION - MECHANICAL STRESS/STRENGTH INTERFERENCE (NONFERROUS), RADC Technical Report 68-403, Rome Air Development Center, Griffiss AFB, New York, February 1969.

9. Kecocioglu, D. B., and Vincent, R. L., RELIABILITY APPROACH TO ROTATING-COMPONENT DESIGN, NASA Technical Note D-7846, National Aeronautics and Space Administration, Washington, D. C., February 1975.

10. Haugen, E. B., and Wirsching, P. H., PROBABILISTIC DESIGN, Machine Design, 15 April - 12 June 1975.

11. Knudsen, G. E., and Keating, J. R., HELICOPTER DRIVE SYSTEM ON-CONDITION MAINTENANCE CAPABILITY (UH-1/AH-1), Bell Helicopter Company; USAAMRDL Technical Report 75-52, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, July 1976, AD A028032.

12. Brand, W. E., Humphrey, R. L., and Diani, J. P., CRITICAL PARTS PROGRAM, UH-1H, AH-1G, OH-6A, OH-58A, CH-47, AND CH-54 AIRCRAFT, Parks College of St. Louis University; USAAVSCOM Technical Report 75-42, U. S. Army Aviation Systems Command, St. Louis, Missouri, 22 August 1975, AD A016126.

13. Knudsen, G. E., and Carr, P. V., R&M DATA ANALYSIS OF THE UH-1/AH-1 TAIL ROTOR SYSTEM, Bell Helicopter Company; USAAMRDL Technical Report 74-11, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1974, AD 782858.

14. Cook. T. N., Starses, F. E., and Wirth, C. J., DESIGN OF SELECTED HELICOPTER COMPONENTS FOR EASE OF REPAIR, Kaman Aerospace Corporation; USAAMRDL Technical Report 76-34, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, December 1976, AD A035152.

15. Rummel, K. G., HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS - VOLUME I, STUDY RESULTS, Boeing Vertol Company; USAAMRDL Technical Report 71-18A, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1971, AD 725595.

16. Burroughs, L. R., Stolper, E., and Hawkins, R., HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS, Sikorsky Aircraft Division, United Technologies Corporation; USAAMRDL Technical Report 71-74, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, February 1972, AD 742248.

17. Burroughs, L. R., STUDY OF HELICOPTER TRANSMISSION SYSTEM DEVELOPMENT TESTING - FINAL REPORT, Sikorsky Aircraft Engineering Report 50547, Sikorsky Aircraft Division, United Technologies Corporation, Stratford, Connecticut, November 1968.

18. Paizen, E., MODERN PROBABILITY THEORY AND ITS APPLICATION, New York, John Wiley and Sons, Inc., December 1964, p. 248.

19. Vogel, A. R., CONCEPT FORMULATION STUDY FOR AUTOMATIC INSPECTION, DIAGNOSTIC, AND PROGNOSTIC SYSTEM (AIDAPS), Northrop Corporation; USAAVSCOM Technical Report 72-20, U. S. Army Aviation Systems Command, St. Louis, Missouri, December 1971, AD 752889.

BIBLIOGRAPHY

1. Bamberger, E. N., et al., LIFE ADJUSTMENT FACTORS FOR BALL AND ROLLER BEARINGS, American Society of Mechanical Engineers, New York, 1971.

2. Tallian, T. E., et al., ROLLER BEARING DAMAGE ATLAS, SKF Industries, Inc., King of Prussia, Pa., 1974.

3. Dalal, H., et al., PROGRESSION OF SURFACE DAMAGE IN ROLLING CONTACT FATIGUE, SKF Industries, Inc.; Office of Naval Research, Washington, D. C., April 1974.

4. Gardner, G. and Cormier, K., 3000-HP ROLLER GEAR TRANSMISSION DEVELOPMENT PROGRAM, Sikorsky Aircraft; USAAMRDL Technical Report 73-98A, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1977, AD A037308.

5. DeBruyne, Neil A., DESIGN AND DEVELOPMENT TESTING OF FREE PLANET TRANSMISSION CONCEPT, Curtiss-Wright Corporation; USAAMRDL Technical Report 74-27, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1974, AD 782857.

6. Hayden, T. S. and Keller, C. H., DESIGN GUIDE FOR HELICOPTER TRANSMISSION SEALS, Sikorsky Aircraft, NASA Lewis Research Center, Cleveland, and U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, 1975.

7. Kish, J., HELICOPTER FREEWHEEL UNIT DESIGN GUIDE, Sikorsky Aircraft; USAAMRDL Technical Report 77-18, Applied Technology Laboratory, U. S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, October 1977, AD A047559.

8. Holbert, C., OPERATIONAL RELIABILITY/MAINTAINABILITY ENGINEERING PROGRAM, ACCOMPLISHMENT REPORT, Sikorsky Aircraft, SER-64340, Revision Z, 1 July 1974 (CH-54B).

9. Holbert, C., OPERATIONAL RELIABILITY/MAINTAINABILITY ENGINEERING PROGRAM, ACCOMPLISHMENT REPORT, Sikorsky Aircraft, SER-64272-1, Revision J, 15 July 1970 (CH-54A).

10. Holbert, C., OPERATIONAL RELIABILITY/MAINTAINABILITY ENGINEERING PROGRAM, QUARTERLY EVALUATION REPORT, Sikorsky Aircraft, SER-64344, Revision K, 15 May 1974 (CH-54B).

11. Holbert, C., OPERATIONAL RELIABILITY/MAINTAINABILITY ENGINEERING PROGRAM, QUARTERLY EVALUATION REPORT, Sikorsky Aircraft, SER-64296, Revision J, 15 December 1970 (CH-54A).

12. Cook, T. N., Young, R. C., and Starses, F. E., MAINTAINABILITY ANALYSIS OF MAJOR HELICOPTER COMPONENTS, Kaman Aerospace Corporation; USAARMDL Technical Report 73-43, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, August 1973, AD 769941.

13. AMC Pamphlet 706-134, ENGINEERING DESIGN HANDBOOK - MAINTENANCE GUIDE FOR DESIGN.

14. Cook, T. N., Starses, F. E., and Haire, G. W., ARMY AIRCRAFT SUBSYSTEM AND COMPONENT INSTALLATION DESIGN INVESTIGATION, Kaman Aerospace Corporation; USAAMRDL Technical Report 75-7, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, February 1975, AD A007245.

15. Loretz, N. F., AIDAPS PROGRAM - FIRST INTERIM TECHNICAL REPORT, AiResearch Manufacturing Co.; USAAVSCOM Contract DAAJ01-73-C-0874, U. S. Army Aviation Systems Command, St. Louis, Missouri, 30 December 1973.

16. Loretz, N. F., AIDAPS PROGRAM - SECOND INTERIM TECHNICAL REPORT, AiResearch Manufacturing Co.; USAAVSCOM Contract DAAJ01-73-C-0874, U. S. Army Aviation Systems Command, St. Louis, Missouri.

17. Loretz, N. F., AIDAPS PROGRAM - THIRD INTERIM TECHNICAL REPORT, AiResearch Manufacturing Co.; USAAVSCOM Technical Report 75-15, U. S. Army Aviation Systems Command, St. Louis, Missouri, 1 April 1975.

18. Loretz, N. F., AIDAPS PROGRAM - FOURTH INTERIM TECHNICAL REPORT, AiResearch Manufacturing Co.; USAAVSCOM Contract DAAJ01-73-C-0874, U. S. Army Aviation Systems Command, St. Louis, Missouri, 1 August 1975.

19. Murphy, J. A., REPORT OF VISIT BY J. A. MURPHY TO MECHANICAL TECHNOLOGY, INC., LATHAM, NEW YORK, 2 APRIL 1975, Bell Helicopter Memo 81:JAM: peb-89, Bell Helicopter Company, Fort Worth, Texas, 23 April 1975.

20. Shives, T. R., and Willard, W. A., DETECTION DIAGNOSIS AND PROGNOSIS, Institute for Materials Research, Washington, D. C.; Proceedings of the 18th Meeting of the Mechanical Failures Prevention Group, Gaithersburg, Maryland, 8-10 November 1972.

21. Skala, G. F., THE IN-LINE OIL MONITOR AND ITS ROLE IN ENGINE CONDITION MONITORING, Environment/One Corporation; presented at the Symposium on Instrumentation for Airbreathing Propulsion, Naval Postgraduate School, Monterey, California, September 1972.

22. Taylor, T., LeVarn, M., and O'Connell, J., PERFORMANCE MONITORING AND FAULT DIAGNOSTICS OF COMMAND AND CONTROL SYSTEMS, RCA Engineer, Vol. 19, February - March, 1974, p. 56-62.

23. Butcher, Robert R., et al., UH-1 TEST BED PROGRAM - FINAL REPORT, Northrop Corporation; USAAVSCOM Technical Report 72-19, U. S. Army Aviation Systems Command, St. Louis, Missouri, June 1972, AD 752891.

24. Provenzano, James, et al., UH-1 AIDAPS TEST BED PROGRAM, Hamilton Standard; USAAVSCOM Technical Report 72-18, U. S. Army Aviation Systems Command, St. Louis, Missouri, August 1972, AD 752894.

25. Beerbower, A., MECHANICAL FAILURE PROGNOSIS THROUGH OIL DEBRIS MONITORING, Exxon Research and Engineering Company; USAAMRDL Technical Report 74-100, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1975, AD A006190.

26. Botstiber, D. W., TRANSMISSION RELIABILITY THROUGH OIL MONITORING, Technical Development Co., Glenolden, Pa.; In Proceedings of The American Helicopter Society, American Institute of Aeronautics and Astronautics, and University of Texas, Joint Symposium on Environmental Effects on VTOL Designs, Arlington, Texas, 16-18 November 1970.

27. Darlow, M. S., Badgley, R. H., and Hogg, G. W., APPLICATION OF HIGH FREQUENCY RESONANCE TECHNIQUES FOR BEARING DIAGNOSTICS IN HELICOPTER GEARBOXES, Mechanical Technology Incorporated; USAAMRDL Technical Report 74-77, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, October 1974, AD A004014.

28. George, John A., et al., PARKS COLLEGE UH-1H AIDAPS PROGRAM - EFFECTS OF MAINTENANCE ACTIONS ON DIAGNOSTIC SIGNATURES, Parks College of St. Louis University; USAAVSCOM Technical Report 74-57, U. S. Army Aviation Systems Command, St. Louis, Missouri, February 1975, AD A008002.

29. Glasser, W. A., Newman, F. D., and Snediker, D. K., THE APPLICATION OF OIL ANALYSIS TECHNIQUES TO THE DIAGNOSIS OF CONDITION AND PREDICTION OF FAILURE IN U. S. ARMY CONSTRUCTION VEHICLES, Battelle Columbus Laboratories; Final Report, November 1973.

30. Hollinger, R. H., ADVANCED CAPACITATIVE OIL DEBRIS MONITOR, Franklin Institute Research Laboratories; USAAMRDL Technical Report 73-53, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, August 1973, AD 772948.

31. Hollinger, R. H., METALLIC DEBRIS MONITOR FOR RECIRCULATING LUBRICATING OIL, Franklin Institute Research Laboratories; USAAMRDL Technical Report 72-10, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1972, AD 745205.

32. Houser, D. R., and Drosjack, M. J., VIBRATION SIGNAL ANALYSIS TECHNIQUES, Ohio State University Research Foundation; USAAMRDL Technical Report 73-101, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, December 1973, AD 776397.

33. Howard, P. L., APPLICATION OF SHOCK PULSE TECHNOLOGY AND VIBRATION ANALYSIS TO ROLLING BEARING CONDITION MONITORING, SKF Industries, Inc.; published in Advances in Test Measurement, proceedings of the Twentieth International Instrumentation Symposium, Volume 11, Instrument Society of America, Pittsburgh, Pennsylvania, 1974, pp. 231-238.

34. House, Thomas, L., Welner, Victor W., RELIABILITY AND MAINTAINABILITY ISSUES IN HELICOPTER PROPULSION AND DRIVE SYSTEM DESIGN, proceedings of the 32nd Annual National Forum, American Helicopter Society, Washington, D. C., May 1976.

35. Wierenga, B. B., et al., ANALYSIS OF ARMY HELICOPTER INSPECTION REQUIREMENTS, RCA Government and Commercial Systems; USAAMRDL Technical Report 72-35, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, September 1972, AD 754642.

36. Blake, D. O., et al., HELICOPTER INSPECTION DESIGN REQUIREMENTS, RCA Government and Commercial Systems; USAAMRDL Technical Report 73-22, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, May 1973, AD 769061.

37. Calhoon, et al., INVESTIGATION OF INSPECTION AIDS, RCA Government and Commercial Systems; USAAMRDL Technical Report 74-44, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, July 1974, AD 787333.

38. Aronson, R. B., HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS - VOLUME II, STUDY PARAMETERS INTERRELATIONSHIP, Boeing-Vertol; USAAMRDL Technical Report 71-18B, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, February 1972, AD 741377.

39. Jines, R. H., HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS - VOLUME III, SENSITIVITY ANALYSIS, Boeing-Vertol; USAAMRDL Technical Report 71-18C, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, February 1972, AD 742247.

40. Bowen, C. W., and Walker, R. R., TRADEOFF STUDY FOR EXTENDED-LIFE HELICOPTER TRANSMISSION, Bell Helicopter Co.; USAAMRDL Technical Report 72-40, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, November 1972, AD 758465.

41. Cormier, K., and Kish, J., HELICOPTER TRANSMISSION MODULARIZATION AND MAINTAINABILITY ANALYSIS, Sikorsky Aircraft; USAAMRDL Technical Report 73-82, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1974, AD 775834.

42. Clark, M. W., et al., IDENTIFICATION AND ANALYSIS OF ARMY HELICOPTER RELIABILITY AND MAINTAINABILITY PROBLEMS AND DEFICIENCIES, VOLUMES I-IV, American Power Jet Company; USAAMRDL Technical Reports 72-11A, B, C, and D, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1972, AD 901456L, 901457L, 901458L, 901459L.

43. Whittaker, I. C., DEVELOPMENT OF TITANIUM AND STEEL FATIGUE VARIABILITY MODEL FOR APPLICATION OF RELIABILITY ANALYSIS APPROACH TO AIRCRAFT STRUCTURES, AFML Technical Report 72-236, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

44. Whittaker, I. C., and Besuner, P. M., A RELIABILITY ANALYSIS APPROACH TO FATIGUE LIFE VARIABILITY OF AIRCRAFT STRUCTURES, AFML Technical Report 69-65, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

APPENDIX A

RELIABILITY ANALYSIS

INTRODUCTION

Reliability is the probability that an item will perform its intended function for a specified interval under stated conditions. The purpose of this analysis is to find analytical techniques that could be used for designing reliability into drive system components to meet specified requirements. Current drive system reliability problems were examined to see where quantitative and qualitative relationships could be applied. Certain techniques appear feasible for expressing reliability in design parameters such as stress. However, considerably more effort is required before such an approach could be fully implemented. Other techniques performed early in the design stage can provide the design engineer with upper and lower bounds of reliability, thus providing an indication of the adequacy of the design with respect to the goal as well as the areas where design changes will have the greatest impact.

DATA BASE

USAAMRDL has conducted extensive reliability studies on current Army helicopter drive systems. The field experience data contained in these studies formed a data bank for this program. Table A-1 shows the data available for each drive system component by aircraft model. As can be immediately seen, no data was available for analysis of OH-6 and OH-58 drive systems. Data for the CH-54 drive system was obtained by reviewing Disassembly Inspection Summaries and Discrepancy/Corrective Action forms available at the Sikorsky Aircraft overhaul facility.

Mission reliability data is more scarce for most models. No data was available for pre-launch mission aborts. This is due to the fact that there is no means for reporting it with The Army Maintenance Management System (TAMMS). Only precautionary landings are reported by the U. S. Army Agency for Aviation Safety (USAAAVS). These data were reviewed only for determining the general criteria under which precautionary landings were made. Except for the CH-54, no data appears to be available for those missions where the primary mission fucntion was not completed, the mission was discontinued, and a routine landing made back at the home base.

[11] Knudsen, G. E., and Keating, J. R., HELICOPTER DRIVE SYSTEM ON-CONDITION MAINTENANCE CAPABILITY (UH-1/AH-1), Bell Helicopter Company; USAAMRDL Technical Report 75-52, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, July 1976, AD A-28032.

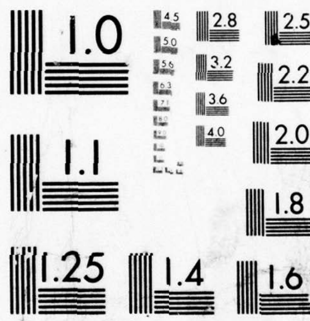
AD-A069 691 UNITED TECHNOLOGIES CORP STRATFORD CT SIKORSKY AIRCR--ETC F/G 1/3
HELICOPTER DRIVE SYSTEM R AND M DESIGN GUIDE.(U)
APR 79 K R CORMIER, B TRUSTEE DAAJ02-76-C-0047

UNCLASSIFIED SER-510012 USARTL-TR-78-51 NL

2 OF 2

AD
A069691

END
DATE
FILMED
7--79
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

TABLE A-1. RELIABILITY DATA BANK	
DATA SOURCE	AIRCRAFT
Main Transmission	
Bowen, C. W., Dyson, L. L., and Walker, R. D., Bell Helicopter Company; MODE OF FAILURE INVESTIGATIONS OF HELICOPTER TRANSMISSIONS, USAAVLABS Technical Report 70-66, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1971, AD 881610.	H-1
Clark, M. W., Krauss, W. K., and Ciccotti, J. M., American Power Jet Company; IDENTIFICATION AND ANALYSIS OF ARMY HELICOPTER RELIABILITY AND MAINTAINABILITY PROBLEMS AND DEFICIENCES-VOLUME II, UTILITY, ATTACK AND TRAINING HELICOPTERS (UH-1, AH-1, TH-1), USAAMRDL Technical Report 72-11B, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, April 1972, AD 9014576.	H-1
Forward, Aft Rotor Transmission; Engine Combining Transmission	
Rummel, K. G., HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS, Volume I, Study Results, Boeing Vertol Company; USAAMRDL Technical Report 71-18A, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1971, AD 725595.	CH-47
Jones, R., ANALYSIS OF CH-47C TRANSMISSION BEARINGS, Boeing-Vertol Report D20-11036-1, Boeing-Vertol Company, Philadelphia, Pennsylvania, March 1976.	CH-47
USAAVLABS Technical Report 70-66.	CH-47
Intermediate Gearbox/42° Gearbox	
Knudsen, G. E., and Carr, P. V., R&M DATA ANALYSIS OF THE UH-1/AH-1 TAIL ROTOR SYSTEM, USAAMRDL Technical Report 74-11, Bell Helicopter Company; Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1974, AD 782858.	H-1

TABLE A-1. (Continued)

DATA SOURCE	AIRCRAFT
Tail Rotor Gearbox/90° Gearbox	
USAAMRDL Technical Report 74-11	H-1
USAAMRDL Technical Report 72-11B.	H-1
Drive Shaft, Couplings, and Support Bearings	
Barrett, L. D., and Aronson, R. B., RELIABILITY AND MAINTAINABILITY PROGRAM FOR SELECTED SUBSYSTEMS AND COMPONENTS OF CH-47 AND UH-1 HELICOPTERS, Boeing-Vertol Report D210-10846-1; U. S. Army Aviation Systems Command, St. Louis, Missouri, September 1974.	CH-47, UH-1
USAAMRDL Technical Report 74-11.	H-1

FAILURE MODES

The Helicopter Drive System R&M Design Guide is concerned with safety-of-flight, mission reliability, and dynamic component removal failure modes. The criteria for defining these are presented in Table A-2.

TABLE A-2. FAILURE MODE CATEGORIZATION CRITERIA

Category	Description
Safety-of-Flight Failure Mode	A failure mode that causes either immediate forced landing, injury to the crew, or catastrophic loss of the vehicle.
Mission Reliability Failure Mode	A failure mode that prevents commencement or completion of a mission, either by rendering the system incapable of performing the primary function of the mission or by exposing the vehicle occupants to unacceptable flight risk if the mission is begun or continued.
Dynamic Component Removal Failure Mode	A failure mode that causes the removal of a component and replacement with a like item.

While these criteria may at first seem definitive, the definition of a failure is still dependent on the judgment of maintenance and operating personnel. In-flight mission aborts* are often caused by a chip light indication. These frequently are chip detector system malfunctions rather than a gearbox malfunction, as shown by Table A-3. Even those instances of "proper indication" are only an opinion of maintenance personnel. Except for situations where visual inspection allows confirmation, premature gearbox removals cannot be confirmed by aircraft maintenance personnel. Gearboxes that are prematurely removed are frequently still operable. Furthermore, failure mode conditions occur concurrently and, as noted by Reference 11, "... are, in the main, evidenced by gradual deterioration." This leads to parts replacement whenever it is suspected that a part's condition will deteriorate to unacceptable levels in the next TBO without any attempt to establish if the part could still function.

Army helicopters are exposed to a variety of operational, maintenance, natural, and induced environments. As can be naturally expected, transmission components are exposed to conditions that may not be in accordance with the approved operational and maintenance procedures and design specification. An example of this is noted in Reference 13 with regard to the UH-1H and AH-1G.

"Although the operator's manuals restricted the engine power to 1100 hp, the engine had output torque values equivalent to 1400 hp at 6600 rpm for military rating and 1250 hp at 6600 rpm for normal rating. The 1100 shp was frequently exceeded when the aircraft were operated under the stress of combat conditions."

While increased corrective maintenance resulted from this severe treatment, any premature gearbox removals that may have been necessary would not be chargeable as a failure for the purpose of reliability calculations. For these to be considered potential failures, the specified power spectrum

---

*A condition, not necessarily a material failure, which prevents sucessful mission completion.

[11] Knudsen, G. E., and Keating, J. R., HELICOPTER DRIVE SYSTEM ON-CONDITION MAINTENANCE CAPABILITY (UH-1/AH-1), Bell Helicopter Company; USAAMRDL Technical Report 75-52, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, July 1976, AD A028032.

[13] Knudsen, G. E., and Carr, P. V., R&M DATA ANALYSIS OF THE UH-1/AH-1 TAIL ROTOR SYSTEM, Bell Helicopter Company; USAAMRDL Technical Report 74-11, Eustis Directorage, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1974, AD 782858.

TABLE A-3. CHIP DETECTOR ANALYSIS SUMMARY [12]

Characteristics	UH-1H Main G/B	UH-1H 90^o G/B	AH-1G Main G/B	AH-1G 90^o G/B	OH-6A Main G/B	OH-6A T/R G/B	OH-58 Main G/B	OH-58 T/R G/B
Proper Indication	25	36	5	5	27	8	17	12
Chip Detector System Malfunction	15	20	3	5	10	1	23	22
Undetermined	10	22	2	5	10	3	3	1
TOTAL	50	78	10	15	47	12	43	35

12 Brand, W. E., Humphrey, R. L., and Diani, J. P., CRITICAL PARTS PROGRAM, UH-1H, AH-1G, OH-6A, OH-58A, CH-47, AND CH-54 AIRCRAFT, Parks College of St. Louis University; USAAVSCOM Technical Report 75-42, U. S. Army Aviation Systems Command, St. Louis, Missouri, 22 August 1975, AD A016126.

must reflect the intended operational use. Elements of the natural and induced environment are given in Table A-4. The definition of failure will only consider the specified operational, maintenance, natural, and induced environments as stated conditions.

The above example is not intended to suggest that when approved operational and maintenance procedures are used, failures do not result. As will be seen later, maintenance-induced problems, when approved procedures are followed, are a source of drive system failures.

Summarizing, a failure is defined as those instances where an engineering analysis has been able to indicate that a part's condition is no longer acceptable for it to continue to perform its intended function under the specified operational, maintenance, natural, and induced environments.

TABLE A-4. NATURAL AND INDUCED ENVIRONMENT ELEMENTS

Natural Environment	Induced Environment
Ambient Temperature	Vibration
Humidity	Transportation and Storage Constraints
Precipitation (all types)	Temperature Shock
Vegetation	Ozone (aircraft induced)
Fungus	Mechanical Shock (all causes)
Soil Particles	Aircraft Fluid Compatibility
Solar Radiation	Cleaning Materials and Techniques
Atmospheric Pressure	Salt Spray
Salt Spray and Sea Salt Fallout	Temperature
Ice	Moisture
Temperature Shock	Overtorque
Ozone (naturally occurring)	Inefficient Inspection Procedures

RELIABILITY REQUIREMENTS

In evaluating drive system reliability, each primary failure mode must be categorized in accordance with the cirteria of Table A-2. The criteria are translated into effects on drive system performance so that it can be applied to individual component performance. Those failure modes that may result in the loss of main rotor power, tail rotor power, or complete loss of all hydraulic and electrical power are tentatively classified as a safety-of-flight failure mode. Failure modes that can be detected with fault warning systems that give the pilot ample warning of impending failure are recategorized as a mission reliability failure.

One observation can be made from the above criteria: the ability to meet mission reliability requirements is heavily dependent on fault warning system reliability and its capability for proper diagnosis of impending drive system failures.

For drive system components other than gearboxes, the criteria for determining mission reliability failures is not explicit. In-flight mission reliability failures that expose the vehicle occupants to unacceptable flight risk if the mission is continued cannot be defined, since they are based on pilot judgment of the particular circumstances that are present. As a result, it is recommended that mission reliability failures for components other than gearboxes be considered those failures which are not safety-of-flight failures but do represent a loss of component function.

Dynamic component removals exclude those drive system failures that are on-aircraft repairable. These repairs, as noted by Reference 14 ".... involve very limited disassembly, primarily the replacement of readily removable parts, such as lip seals and sight glasses".

Reliability requirements for drive system components or assemblies are obtained by combining the reliability characteristics of the individual parts that comprise it. The reliability of parts are related to the reliability of components/assemblies by the product of the individual part reliability that comprise the component/assembly. This means that all parts of an assembly or a component must function properly for the assembly or component to function properly. Similarly, if a part has more than one primary failure mode, there must be no occurrences of any primary failure mode for the part to function properly. As a result, the component/assembly reliability is equated to the product of individual part failure mode reliabilities.

---

[14] Cook, T. N., Starses, F. E., and Wirth, C. J., DESIGN OF SELECTED HELICOPTER COMPONENTS FOR EASE OF REPAIR, Kaman Aerospace Corporation; USAAMRDL Technical Report 76-34, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, December 1976, AD A035152.

Reliability requirements are usually specified in terms of an average failure rate or mean time between failure for a given failure category (dynamic component removal, mission abort, etc.). For drive systems maintained without any scheduled overhauls (on-condition), the relationship between reliability for the particular category failure and the mean time between failure event is given by

$$MTBF = \int_0^\infty R(t)\,dt \qquad (A-1)$$

where

MTBF = the mean time failure for a particular category

R(t) = the reliability associated with the particular category

The integral in Equation (A-1) does not generally result in a closed mathematical expression. If an exact solution is desired, the integral must be evaluated by numerical methods using a digital computer. An exception to this general case is when R(t) is described by the Weibull reliability function. In this case, Equation (A-1) becomes

$$MTBR = \Theta \cdot \Gamma\ (1 + 1/\beta) \qquad (A-2)$$

where

β, Θ = the size and shape parameters associated with R(t)

$\Gamma(1+1/\beta)$ = the gamma function for $(1 + 1/\beta)$

Since future Army drive systems will be designed for on-condition maintenance, the primary reliability requirement will be the Mean Time Between Removal (MTBR). Consequently, if Equation (A-2) is confined to failures that require drive system component removal, the MTBR is simply equal to the MTBF.

A study of existing gearboxes was undertaken to determine what reliability distribution could be used to describe overall gearbox reliability. The hazard function parameters given in the design guide were used to determine values of R(t) for values of t between 100 hours and 10,000 hours. Each value of R(t) was calculated from Equation (A-3), which results from the reliability being equated to the product of individual part failure mode reliabilities.

$$F(t) = e^{-\Sigma(t/\Theta_i\ )^{\beta_i}} \qquad (A-3)$$

Results were then plotted on Weibull paper. A typical plot is shown in Figure A-1. It should be noted how close the points are to the straight line Weibull reliability distribution. The MTBR associated with the straight line was calculated using Equation (A-2) and compared to that calculated for the individual points from Equation (A-1). In all cases, the results were found to be within 5 percent of each other.

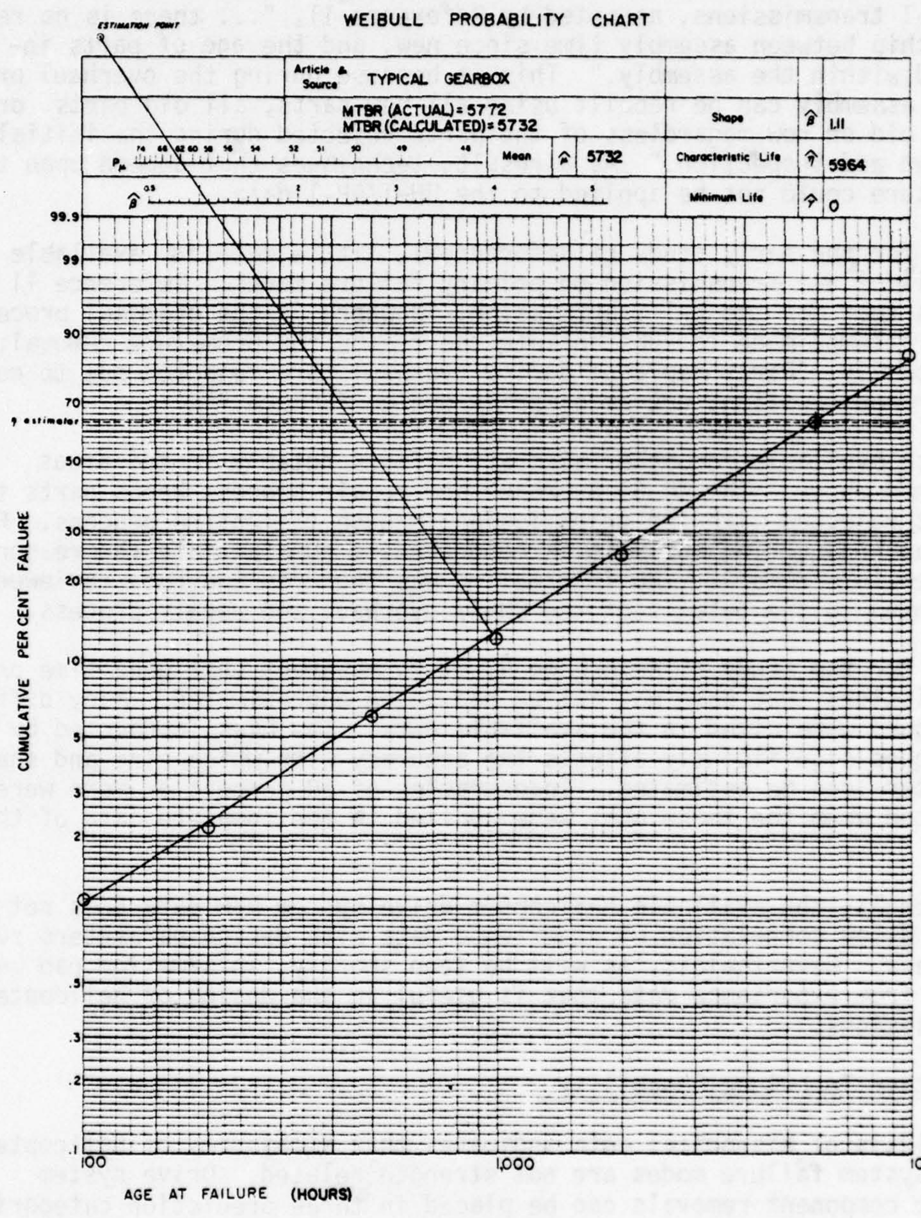


Figure A-1. Typical Weibull Plot.

GENERAL DISCUSSION

Data Availability

Initially the available data were reviewed to extract hazard function parameters of past Army drive train components. It was found that for the UH-1 transmissions, as noted by Reference 11, "... there is no relationship between assembly time since new, and the age of parts installed within the assembly." This is because during the overhaul process "...an assembly can be rebuilt using all new parts, all old parts, or any mix of old or new regardless of the parts rejected during the initial teardown and inspection." As a result, techniques that depend upon time-to-failure could not be applied to the UH-1/AH-1 data.

Except for the early study of Reference 1, little data is available for analysis of H-1 transmission on primary failure modes. Reference 11 indicates that for the H-1 transmission, "Nowhere in the overhaul process is any attempt made to substantiate the reason for premature removal." Additionally, "Parts replaced during overhaul are rejected due to condition or modification, not necessarily due to failure."

The data available for other aircraft differs notably in the areas mentioned above. The CH-54 overhaul and repair process keeps parts that are not rejected with the transmission through the entire process. Furthermore, an engineering analysis is conducted to substantiate the reason for the premature removal. No information was found in the data reviewed pertaining to the details of the CH-47 overhaul and repair process.

Except for the study of Reference 5, it is apparent that good time on transmissions that have not failed had to be approximated. Many different techniques were cited in the available data. The bias introduced by these techniques significantly affects the accuracy with which size and shape parameters can be estimated. Inaccuracies of 20 percent or more were experienced when the techniques were applied to the complete data of the CH-54.

As a result, the available helicopter drive system R/M data does not generally allow correlation of experience data with design parameters such as stress. Nevertheless, as will be seen shortly, information can be obtained from experience data that is useful in the design of helicopter transmissions.

Prediction Technique Capability

An analysis of historical data indicates that a majority of helicopter drive system failure modes are not strength related. Drive system dynamic component removals can be placed in three prediction categories. These categories are defined as follows:

Category I - Primary failure modes that are principally caused by strength-related failure mechanisms.

Category II - Primary failure modes that are not fundamentally caused by strength-related failure mechanisms but can be predicted by similarity with qualitative features of previous designs.

Category III - Primary failure modes that cannot be predicted because not enough is known about the modes and their causes.

A close examination of available data reveals that many factors in the past were responsible for drive train failures. These include:

- Subsurface fatigue
- Lubrication
- Maintenance
- Assembly during manufacture/overhaul
- Natural environment
- Handling
- Fabrication prior to assembly
- Overload
- Aircraft interface
- Induced environment

The experience gained should not be discarded and can be useful in the design of helicopter transmissions. Table A-5 summarizes these for each major component.

Hazard function analysis, based on historical data, is applicable to failure modes in Categories I and II. The analysis performed early in the design stage can provide the design engineer with upper and lower bounds of the MTBR by considering the design in the light of past experience. Additionally, the hazard function analysis can also show the designer the areas where improvements will have the greatest impact. The technique for statically loaded components is compatible with a constant failure rate, i.e., a constant hazard function. The potential for hazard function analysis predictions is about 70 to 80 percent of gearbox failures, based on the average percentage of failures in Categories I and II after development.

Probabilistic design as it is currently forumulated is applicable to failure modes in Category I, which account for approximately 25 percent of gearbox failures. Probabilistic design requires more development before it is usable as a design tool. It must account for each significant failure mechanism. This means that a number of strength distributions are probably required for each component. Each distribution would probably require more field or test data than an equivalent model, due to the increased number of degrees of freedom involved. Consideration must also be given to variabilities in material properties and tolerances introduced by different part suppliers. It is entirely possible, as indicated by Reference 4 that other than normal distribution, such as the Weibull distribution, would be more applicable for the strength distribution. As a result, computerization of the technique appears necessary for it to be feasible.

TABLE A-5. QUALITATIVE RELIABILITY CONSIDERATIONS

COMPONENT	EXPERIENCE	LESSON
Bearings	Material impurities cause early fatigue pitting of bearings	Use of vacuum degassed and consumable electrode vacuum-melt bearing steel significantly increases bearing life
	Bearing failures are induced by debris damage	Fine filters should be used to reduce the size and number of gearbox contaminants
	During assembly, it is possible to omit parts and still have an assembly that appears functional	Built-up assemblies should be "Murphy-proof" and incorporate features that allow assembly to be checked
Gears	Sharp corners caused by inadequate gear tooth edge break become brittle after nitriding	Amount of gear tooth edge break should be specified on detail drawing
Seals	Shaft seals are responsible for many gearbox removals	Seals should be field replaceable
	Field repairs are done frequently in poor lighting. Leakage results from chipping of the seal from bumping by an item that is being installed in a transmission. Damage cannot be detected until runup.	Installation should preclude damage from sharp corners and edges of mating parts during assembly or reassembly
	Seals deteriorate from exposure to sand	Primary sealing members should be protected from the external environment
	O-rings are cut by sharp corners of mating components during installation	Surfaces and corners contacting O-rings during installation should be smooth
Splines	Loss of lubricant in grease-packed splines leads to spline wear and failure	Use of grease-lubricated splines should be minimized. Lubricant retention features are required for all grease-packed splines

TABLE A.5 (Continued)

COMPONENT	EXPERIENCE	LESSON
Splines (Cont'd)	Dynamic imbalance of drive shaft causes spline wear	Both static and dynamic balancing should be considered for all drive shafts
	Complicated maintenance procedure for installation of hardware is prone to maintenance-induced errors	Built-up assemblies should incorporate features that allow assembly to be checked
	Worn self-locking nuts cause locking hardware to become loose	Positive locking nuts should be used (self-locking features wear) to prevent potential maintenance errors
Lock Nuts	Lock nut backs off of pinion on shaft	Lock nut should have threads engaged. Hand of thread should be selected such that nut tends to tighten during operation. Nylon inserts should not be used since they could flow when the nut is torqued
Lock Washers	Tangs on lock washer worn/broken	Contact surface area should be maximized to minimize wear from fretting
Drive Shaft	Exposure to salt atmosphere leads to shaft corrosion	Provide enclosure for tail drive shaft and drain holes that allow drainage of trapped water
	Inadequate clearance between shaft and surrounding structure allows shaft to be damaged from small tools that may have been dropped or chafed by electrical and hydraulic lines	Nominally a 3-inch clearance is needed between shaft and surrounding structure. Mock-up review should be planned during design phase
Main Rotor Shaft	Shaft plug left off or missing resulting in water contamination of gearbox	Internal shaft plugs should be non-removable in the field

TABLE A-5. (Continued)

COMPONENT	EXPERIENCE	LESSON
Viscous Damper	Bladder filled with wrong fluid	If leaking, viscous damper should be replaced
	Bladder deteriorates from exposure to sand	Enclosure within a tail rotor drive shaft cover reduces the likelihood of this mode
Accessories	Gearbox damaged from handling. Transfer of accessories from one transmission to another creates the potential for incorrect installation	Integral accessories and/or reducing the number of external connections is desirable
Freewheel Unit	Freewheel units where centrifugally fed lubricant is not supplied during overrunning conditions exhibit wear	Pressurized lubrication during overrunning reduces wear substantially
Thomas Couplings	The need for shimming during each installation results in occasional shaft misalignment	Shimming is a potential maintenance error. The need for shimming should be minimized where possible
	When different length bolts are used, incorrect bolts are occasionally installed	Identical length bolts should be used if possible

APPENDIX B

DESIGN SUPPORT AND RELIABILITY DEVELOPMENT TESTS

INTRODUCTION

The relationships between reliability requirements imposed on a transmission system and the development test programs were examined. Previous studies 15, 16, 17, were reviewed for developing a planning procedure that identifies development testing required to obtain reliability requirements at minimum program cost. Two approaches for dealing with reliability growth of helicopter drive systems were explored. The two approaches considered, a generalized test plan and a UTTAS-type test, each have advantages and limitations.

GENERALIZED TEST PLAN

Type of Tests

Three types of tests are used to substantiate the basic design and to provide a demonstration of the capabilities of a transmission system. These tests are categorized as follows:

Type I - General Design Development Tests

These tests confirm that the basic design approach and initial sizing of components are acceptable. These include:

- Bearing and Seal Tests - Develop and verify proper operational characteristics.
- No-load Lubrication Test - Demonstrates satisfactory oil quantity and flow

---

[15] Rummel, K. G., HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS - VOLUME I, STUDY RESULTS, Boeing Vertol Company; USAAMRDL Technical Report 71-18A, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1971, AD 725595.

[16] Burroughs, L. R., Stolper, E., and Hawkins, R., HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS, Sikorsky Aircraft Division, United Technologies Corporation; USAAMRDL Technical Report 71-74, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, February 1972, AD 742248.

[17] Burroughs, L. R., STUDY OF HELICOPTER TRANSMISSION SYSTEM DEVELOPMENT TESTING - FINAL REPORT, Sikorsky Aircraft Engineering Report 50547, Sikorsky Aircraft Division, United Technologies Corporation, Stratford, Connecticut, November 1968.

- Gear Pattern Test - Develops and verifies proper dynamic gear patterns.

- Tiedown Test - Demonstrates performance of aircraft system prior to and during initial flight tests.

- Flight Test - Demonstrates airworthiness of aircraft system.

- Fatigue Tests - Define the fatigue life for various components.

- Static Load Tests - Define static properties of components.

- Single Failure Mode Investigation - Determines susceptibility of various components to a particular failure mechanism.

- Transmission Bench Test - Determines failure modes, detectability of failures, extent of fail-safe features, and "debugs" transmission.

Type II - Reliability Problem Identification Tests

These tests determine the existence, rate, and cause of reliability problems and determine if corrective action is necessary and effective. The costs of these tests vary as a function of reliability levels, the mix of specific test techniques, and the program schedule. They include:

- Endurance Bench Tests - Determine problems that affect reliability objectives.

- Propulsion System/Tiedown Tests - Provide accelerated testing of transmission system.

Type III - Reliability Field Evaluation

This evaluation proves that contractural reliability requirements have been met. As an example, in the UTTAS program, the Army will take a selected number of early production aircraft and determine the MTBR for transmission components over a specified number of flight hours. These values will be compared with Army requirements to determine compliance.

Planning Procedures

The following procedure is designed to provide the lowest cost mix of tests that are needed for transmission development and will give reasonable assurance of passing the reliability requirements. The planned level is always within the initial reliability prediction for the transmission. The procedure developed recognizes the limitation of current reliability prediction techniques to predict values that represent the hardware reliability at a point in time when the hardware is fully developed. Furthermore, the procedure recognizes that test planning requires close coordination between design engineering, test engineering, R&M engineering, and program management.

The procedure consists of four steps. It assumes that the demonstration is a fixed-length test and that individual gearbox operating times are always within its useful life where the failure rate is approximately constant. Only the first step directly involves the transmission designer. The other steps involve R&M engineering, test engineering, and program management respectively. These steps are outlined below.

Step 1

Design Requirements - For a given test length, determine the design MTBR needed to equal or exceed the MTBR to be demonstrated. To make this determination, the following information is needed:

- The value of MTBR to be demonstrated (or equivalently the minimum acceptable MTBR to the customer). This value is denoted as MTBR*.

- Consumer risk - the risk of a gearbox with lesser reliability passing the test. This is denoted as β. The factor $1 - \beta$ is the probability that gearboxes which pass the test have at least the minimum acceptable MTBR.

- Producer risk - the risk of a gearbox failing demonstration when it has the required reliability. This risk is denoted as α The factor $1 - \alpha$ is the probability the contractor has in proving compliance.

- Number of removals, denoted by r, allowed during the demonstration.

- Demonstration period duration, denoted by T, is the total demonstration time on all units.

For a typical case where the MTBR to be demonstrated is 1500 hours, assume the consumer's risk is .1, the producer's risk is .2, the number of removals allowed is 3, and the total test duration is 10,000 hours. It can be seen from Figure B-1 that the design or planned MTBR, denoted as $MTBR_{PLAN}$, needed to pass the reliability demonstration is approximately 4300 hours. $MTBR_{PLAN}$ is the design requirement. Note that a longer demonstration period allows much lower values to $MTBR_{PLAN}$ and less stringent design requirements than shorter demonstration periods. Hence, results are more meaningful and designs less costly.

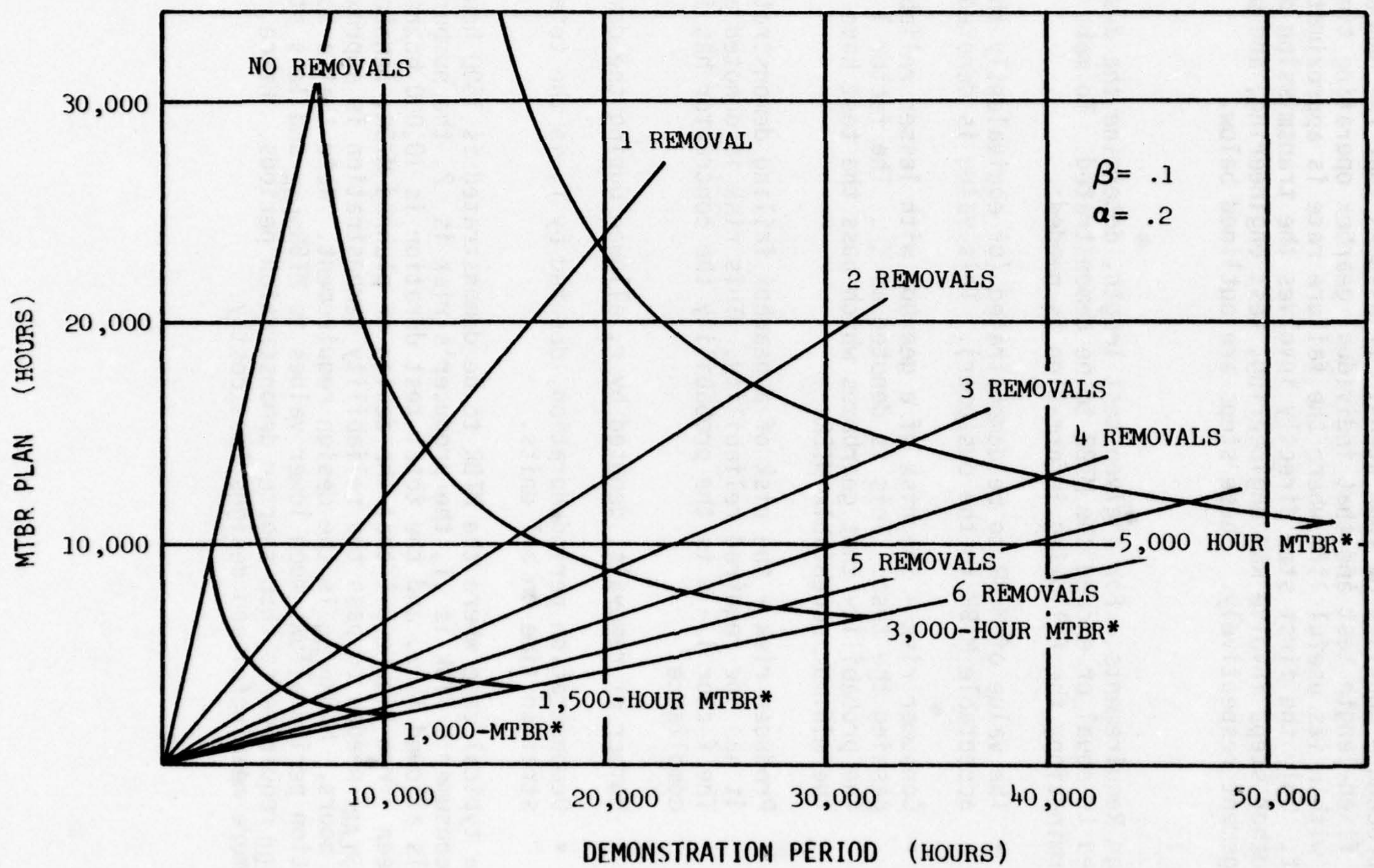


Figure B-1. Determination of Design Requirements

The following procedure was used to calculate the curves shown in Figure B-1 and should be used for values other than those given.

1. Compute a value for the χ^2 (chi-square) distribution based on the total demonstration time available (T) and the minimum acceptable MTBR* by substitution in the following equation:

$$\chi^2_{2r+2,1-\beta} = \frac{2T}{MTBR^*} \tag{B-1}$$

The quantity $\chi^2_{2r+2,1-\beta}$, represents the percentage points of the χ^2 (chi-square) distribution for 2r+2 degrees of freedom or an allowed number of removals (r) and a probability (1-β) that the required minimum acceptable MTBR* exists. Figure B-2 or a table of chi-square statistics can be used to determine values of χ^2.

2. Compute the planned MTBR from the following equation:

$$1 - \alpha = e^{-T/MTBR_{PLAN}} \sum_{i=0}^{r} \frac{\left[T/MTBR_{PLAN}\right]^i}{i!} \tag{B-2}$$

The above equation equates the probability of observing r or less removals with the planned MTBR to the chance of proving compliance using the Poisson probability law. If we let

$$X = \frac{T}{MTBR_{PLAN}}$$

then Equation (B-2) can be reduced as follows:

$$1 - \alpha = e^{-X} \sum_{i=0}^{r} \frac{X^i}{i!} \tag{B-3}$$

Values of X can be found using numerical methods such as iterative techniques. In the event the test allows r to be large, e.g., greater than 10, a normal distribution approximation can be used to find X as follows (Reference 18):

$$Z_{1-\alpha} = \frac{r - X + .5}{\sqrt{X}} \tag{B-4}$$

where $Z_{1-\alpha}$ is the tabulated value for the normal distribution statistic.

---

[18] Paizen, E., MODERN PROBABILITY THEORY AND ITS APPLICATION, New York, John Wiley and Sons, Inc., December 1964, p. 248

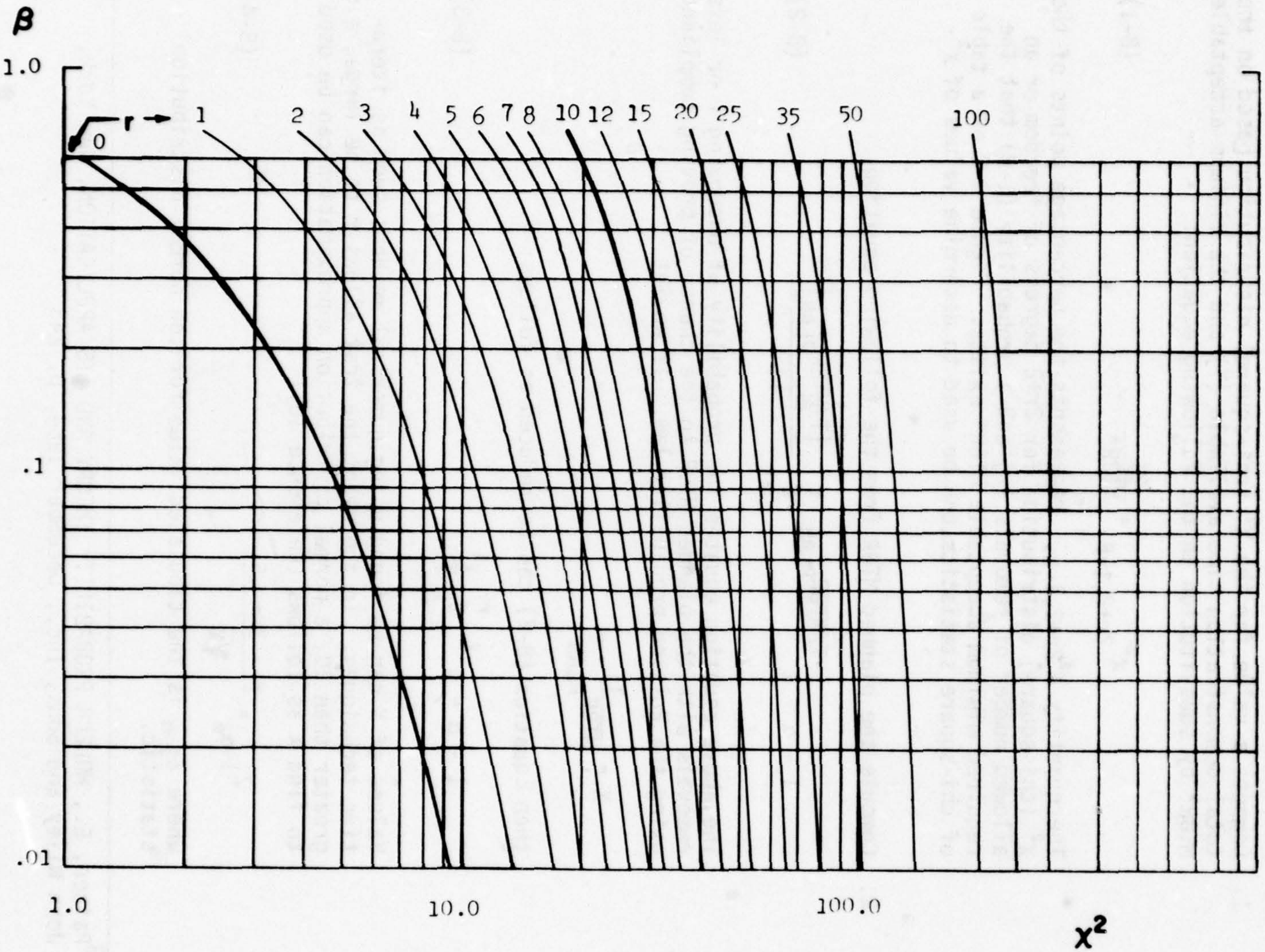


Figure B-2. Chi-Square Statistics.

Equation (B-4) leads to

$$X = \left[\frac{-Z_{1-\alpha} + \sqrt{Z^2_{1-\alpha} \quad + 4(r+.5)}}{2}\right] \qquad \text{(B-5)}$$

Figure B-3 gives values of X for Equations (B-3) and (B-5)

The following illustrative examples will show how the procedure can be used to find the $MTBR_{PLAN}$. Determine the $MTBR_{PLAN}$ for a total test duration of 10,000 hours (T), with a 10-percent consumer risk (β) and a 20-percent producer risk (α) in demonstrating a 1500-hour MTBR*.

1. Equation (B-1) becomes:

$$X^2 \; {}_{2r+2,1-\beta} = \frac{2(10,000)}{1500} = 13.333 \qquad \text{(B-6)}$$

From a table of chi-square statistics, the number of degrees of freedom, 2r+2, for a probability of 90% are 8, or the acceptable number of removals is 3. This result can also be easily obtained from Figure B-2.

2. Substituting this value of r in Equation (B-3), we have:

$$.8 = e^{-X} \left(1 + X + \frac{X^2}{2} + \frac{X^3}{6}\right) \qquad \text{(B-7)}$$

By numerical methods, X is equal to 2.2967 and the $MTBR_{PLAN}$ is 4354 hours. Approximately the same result can be easily obtained from Figure B-3.

Use the same example, changing the demonstration period duration to 50,000 hours.

1. Equation B-1 now yields $X^2_{2r+2,1-\beta} = 66.6667$ and for a probability of 90-percent (β is .1), the allowed number of removals, r, is 25. This result can be obtained from a table of chi-square statistics or Figure B-2.

2. From a table of the cumulative normal distribution functions for a probability of 80-percent (α is .2), the value of $Z_{1-\alpha}$ is .842. Substituting values of 25 and .842 for r and $Z_{1-\alpha}$, respectively, in Equation (B-5), X is equal to 21.59 and the $MTBR_{PLAN}$ is 2316 hours. Figure B-3 can also be used to obtain approximately the same result.

<u>Step 2</u>

Reliability Appraisal - The reliability appraisal consists of examining development history, the influence of the design on this experience, the capability of each test proposed, determining a corrective action policy,

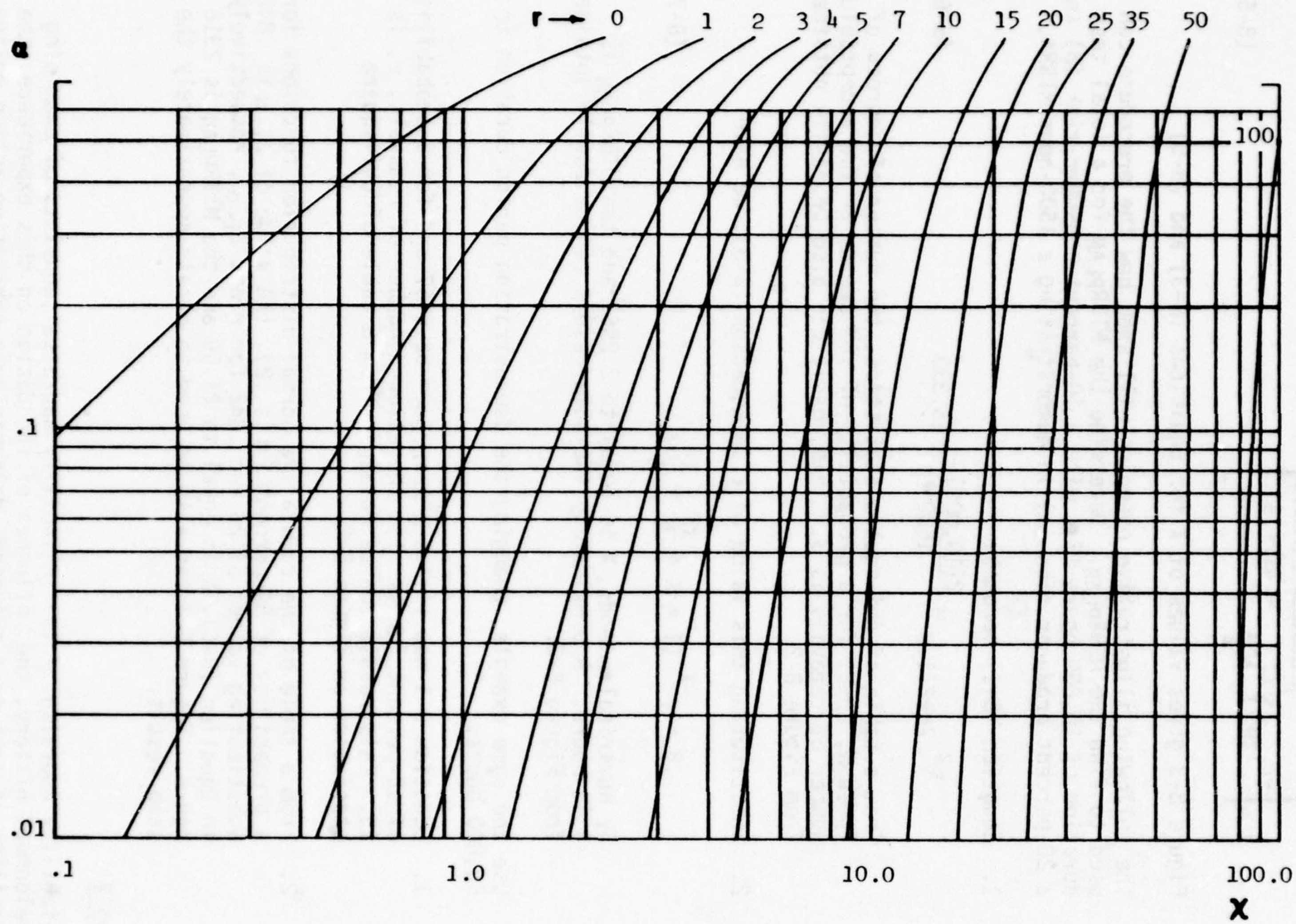


Figure B-3. X Values for Equations (B-3) and (B-5).

and the effectiveness of each test proposed.

1. Development History - Determine development history of a transmission system from an aircraft or approximately the same weight class, size, and power. Appendix II to Reference 15 provides CH-47 main transmission history. References 16 and 17 provide H-3 and early H-53 experience. Include in data base:

   - Potential safety-affecting modes
   - Modes that caused more than two removals
   - Modes with significant maintenance expenditures at depot or field level
   - Modes that caused an unscheduled removal during previous development testing.

2. New Design Influence - Restructure modes in data base as follows:

   - Remove modes that were eliminated by changes in design practices or procedures.
   - Remove modes for design changes that allow them to be considered on-aircraft repairs instead of a removal.
   - Remove modes that can be eliminated as a result of Type I tests.

3. Test Capability - Examine ability of each Type II test to detect failures that would occur in the field based on previous experience. Extend capability previously experienced as follows:

   - Add modes that were undiscovered because of configuration differences*, i.e.

     - Modes were not discovered because they were eliminated by a test performed earlier.

     - Manufacturing or material errors appeared only on one particular test article.

   - Add modes caused by maintenance environment.

   - Revise test acceptance criteria to report those modes that occurred on test but were previously not recorded.

   - Revise test procedures to add modes of operation not previously exercised that could detect failures.

4. Corrective Action Policy - Develop policy for taking corrective action and its effectiveness. This includes:

   - Defining the number of failures that must be observed before action is taken.

---

*Assumes modes are equally likely to occur in any problem identification test.

- The efficiency of each fix in eliminating modes that were observed.

5. Test Effectiveness - Evaluate each test's ability to improve the MTBR as a function of test duration.

Step 3

Test Costs - Determine costs for each test as a function of test duration by considering the following:

- When demonstration is scheduled, i.e., during preproduction program or in early production.
- Total length of test program.
- Lead time needed to prepare test facilities and obtain test articles.
- Number of test rigs and test articles.
- Nonrecurrring and recurring costs.

Step 4

Minimize Program Costs - Determine lowest total test program costs using the data from previous tests. Construct total program test costs as shown in Figure B-4. Demonstration costs are only included if Type III testing is part of preproduction testing.

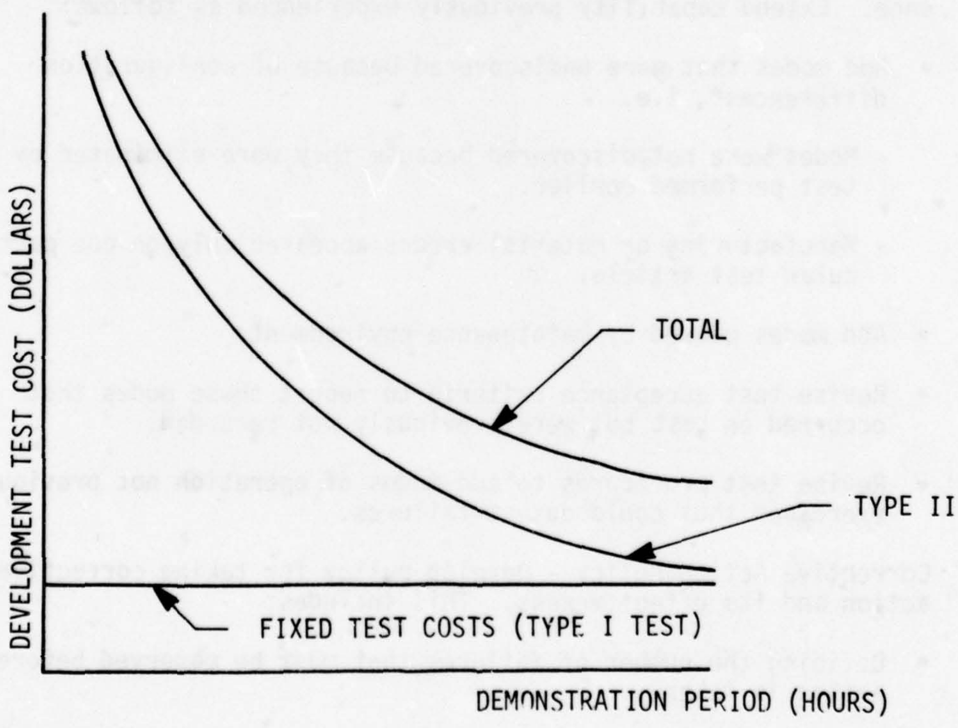


Figure B-4. Program Cost Determination.

UTTAS PROGRAM

The transmission development program for UTTAS has been highly successful. The program for the Basic Engineering Development Phase and the Maturity Phase is outlined in Tables B-1 and B-2. The Army will fly a selected number of early production aircraft and determine the MTBR for transmission components over a specified number of flight hours. These values will be compared with Army requirements to determine compliance.

GENERAL DISCUSSION

The two approaches considered above each have advantages and limitations. In the generalized test plan, test planners or program managers must evaluate the constraints of cost and schedule against changes in the development test requirements. If reliability demonstrations and economic incentives are imposed for production, the approach allows more attention to be focused on reliability. The method may be insensitive to new design techniques or be constrained by particular program considerations. Assumptions as to when corrective action is taken and its efficiency must be further studied in light of past experience. The UTTAS-type program is applicable to programs with the same constraints, and designs with compatible technologies and failure distributions.

Regardless of the approach to reliability development, reliability demonstrations are more economically performed during early production with field experience than during development testing because costs are spread over more units, a better evaluation of the service environment can be performed, and a broader statistical base exists. A demonstration performed during development must be short.

TABLE B-1. UTTAS TRANSMISSION DEVELOPMENT TEST HOUR SUMMARY

COMPONENT/SUBSYSTEM	SUBSYSTEM & GROUND TESTS(HOURS) BENCH	GROUND TEST VEHICLE	FLIGHT HOURS
Main Transmission & Shaft	1815	1900	2949
Engine Shafting	-	3800	5898
Tail Rotor Shafting	-	1900	2949
Intermediate Transmission	1923	1900	2949
Tail Rotor Transmission	1923	1900	2949

TABLE B-2. UTTAS TRANSMISSION DEVELOPMENT SUMMARY

MAIN TRANSMISSION	INTERMEDIATE TRANSMISSION	TAIL ROTOR TRANSMISSION	EXTERNAL SHAFTING COUPLINGS, BEARINGS	BENCH TEST
x	x	x		No-Load Lubrication Test
x				Freewheel Test
x	x	x		Gear Pattern Test
		x		Tail Rotor Output Bevel Gear Static Stress Survey
			x	Tail Rotor Shaft Ballistic Test
			x	Thomas Coupling Stiffness Test
x	x	x		Transmission Housing Static Test
			x	Drive Shaft Viscous Bearing Static Test
x	x	x		Qualification
x	x	x		Lubrication Starvation
				<u>Ground Test</u>
			x	Critical Speed Survey
x		x	x	Military Qualification Test
x		x	x	Endurance/Development Test
				<u>Flight Test</u>
x	x	x	x	Aircraft System Evaluation

APPENDIX C

MAINTAINABILITY ANALYSIS

INTRODUCTION

Corrective maintenance is performed after a failure has occurred to restore an item to a specified condition. Often this requires several levels of maintenance. Figure C-1 shows an example of a UH-1 seal replacment.

The purpose of this analysis was to find an analytical method that would allow the corrective maintenance required at each maintenance level to be calculated and compared with the requirements. Several approaches were explored to determine advantages and limitations of each. As part of this analysis, design features that enhance on-aircraft repairability were examined based on a review of current drive system maintainability problems as well as the impact of a three- level versus four-level organization.

MAINTAINABILITY DATA BASE

USAAMRDL conducted extensive maintainability studies on field repairs of current Army helicopter drive systems. The experience data contained in these studies formed the maintainability data bank for this study. Table C-1 shows the available data for each component by aircraft. While other sources were reviewed for possible inclusion in the data bank, they were omitted because of insufficient definition of the corrective maintenance that was performed.

No data was generally suitable for off-aircraft repairs of drive system components. Much of the available data on off-aircraft repairs does not define the repair sufficiently well to be useful. In only a few cases are tasks well defined for on-aircraft repairs. These include removal and replacment of components listed in Table C-1.

Only one data source reported depot maintenance data, Reference 19. Large discrepancies were noted for the CH-54 between the manhours reported and those experienced at Sikorsky's overhaul facility. Since the differences could not be accounted for, this data was not used. It had been hoped it could be used as a guide for bounding depot maintenance manhours of future designs.

---

[19] Vogel, A. R., CONCEPT FORMULATION STUDY FOR AUTOMATIC INSPECTION, DIAGNOSTIC, AND PROGNOSTIC SYSTEM (AIDAPS), Northrop Corporation; USAAVSCOM Technical Report 72-20, U. S. Army Aviation Systems Command, St. Louis, Missouri, December 1971, AD 752889.

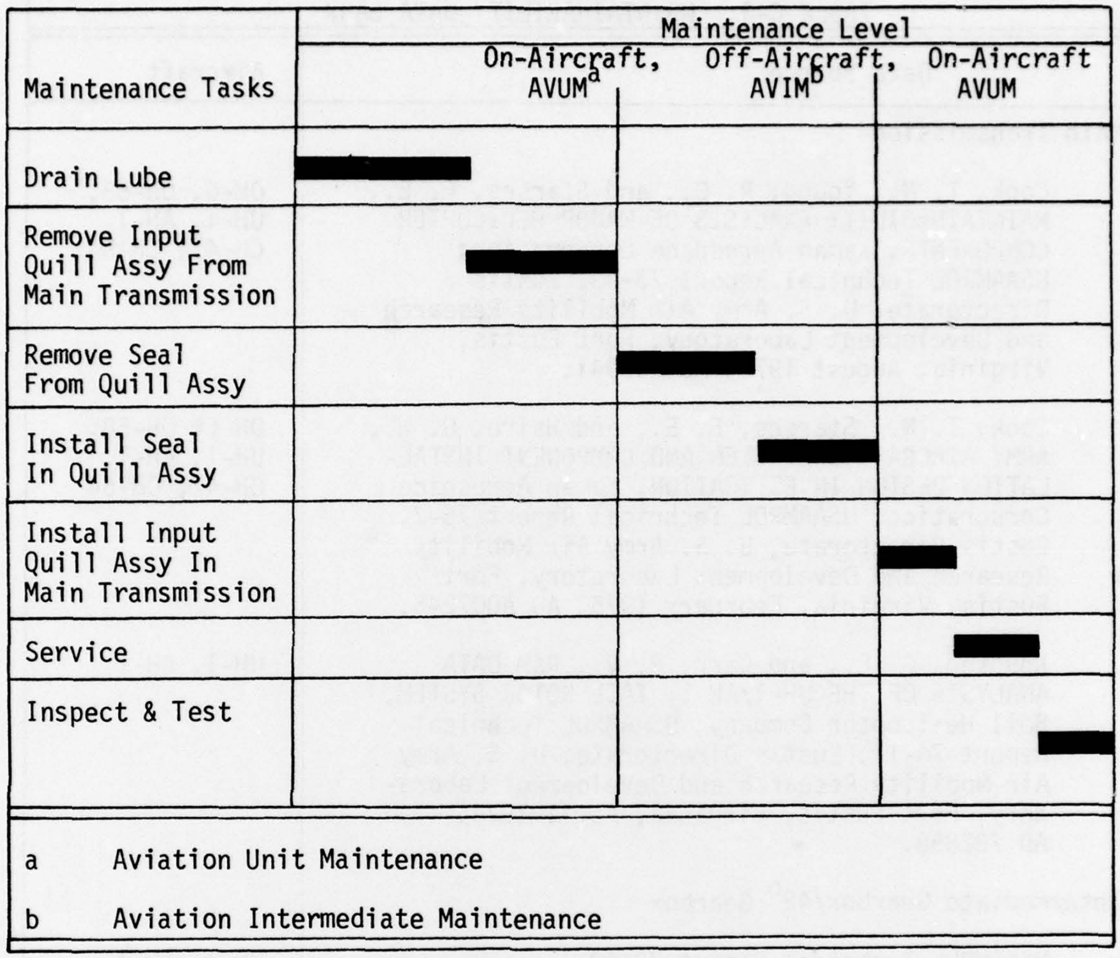


Figure C-1. Time Diagram for Field Replacement of Seal

TABLE C-1. MAINTAINABILITY DATA BANK

Data Source	Aircraft
Main Transmission	
Cook, T. N., Young, R. C., and Starses, F. E., MAINTAINABILITY ANALYSIS OF MAJOR HELICOPTER COMPONENTS, Kaman Aerospace Corporation; USAAMRDL Technical Report 73-43, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, August 1973, AD 769941.	OH-6, OH-58, UH-1, AH-1, CH-47, CH-54
Cook, T. N., Starses, F. E., and Haire, G. W., ARMY AIRCRAFT SUBSYSTEM AND COMPONENT INSTALLATION DESIGN INVESTIGATION, Kaman Aerospace Corporation; USAAMRDL Technical Report 75-7, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, February 1975, AD A007245.	OH-6, OH-58, UH-1, AH-1, CH-47, CH-54
Knudsen, G. E., and Carr, P. V., R&M DATA ANALYSIS OF THE UH-1/AH-1, TAIL ROTOR SYSTEM, Bell Helicopter Company; USAAMRDL Technical Report 74-11, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1974, AD 782858.	UH-1, AH-1
Intermediate Gearbox/42° Gearbox	
USAAMRDL Technical Report 73-43.	UH-1, AH-1, CH-54
USAAMRDL Technical Report 75-7.	UH-1, AH-1, CH-54
USAAMRDL Technical Report 74-11.	UH-1, AH-1
Tail Rotor Gearbox/90° Gearbox	
USAAMRDL Technical Report 73-43.	OH-6, OH-58, UH-1, AH-1, CH-54
USAAMRDL Technical Report 75-7.	OH-6, OH-58, UH-1, CH-54
USAAMRDL Technical Report 74-11.	UH-1, AH-1

TABLE C-1. (Continued)	
Data Source	Aircraft
Drive Shaft	
USAAMRDL Technical Report 73-43.	OH-6, OH-58, UH-1, AH-1, CH-47, CH-54
USAAMRDL Technical Report 75-7.	OH-6, OH-58, UH-1, AH-1, CH-47, CH-54
USAAMRDL Technical Report 74-11.	UH-1, AH-1
Drive Shaft Coupling/Support Bearings	
USAAMRDL Technical Report 73-43.	OH-6, OH-58, UH-1, AH-1, CH-47, CH-54
USAAMRDL Technical Report 75-7.	OH-6, OH-58, UH-1, AH-1, CH-47, CH-54
USAAMRDL Technical Report 74-11.	UH-1, AH-1
Input/Output Drive Shaft Seals	
Cook, T. N., Starses, F. E., and Wirth, C. J., DESIGN OF SELECTED HELICOPTER COMPONENTS FOR EASE OF REPAIR. Kaman Aerospace Corporation; USAAMRDL Technical Report 76-34, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, December 1976, AD A035152.	OH-58, UH-1, AH-1, CH-47, CH-54

ON-AIRCRAFT REPAIRABILITY

An analysis of dynamic component removals has indicated that a major part of any removal is involved with gaining access, removing other components that are mounted on the drive train components, and building up these items when the component is installed. The manbour expenditures of these processes are too large to ignore even though they are primarily not the responsibility of the transmission design engineer. Table C-2 shows how main transmission removal is affected by the above for current Army helicopters. The entire task was divided into elements that represent discrete steps of the task. The entries labeled "inherent" represent the portion of the task for which the transmission designer is responsible. Future helicopter configurations have to focus attention towards minimizing any

TABLE C-2. MAINTENANCE MANHOUR RESPONSIBILITY OF TRANSMISSION DESIGNER

Aircraft	Transmission	Total	Fault/ Isolate	Gain Access/ Secure	Remove/ Install Other Comp.	Remove/ Install Build-up Items[a]	Adjust/ Align Track	Remove/ Install Comp.	Drain/ Lube Service	Inspect and Test
OH-58	Main									
	Inherent	5.3	.4	-	-	-	-	3.5	1.2	.1
	Actual	13.9	.4	2.0	6.7	-	-	3.5	1.2	.1
OH-6	Main									
	Inherent	7.6	.5	-	-	.4	0.6	3.3	1.1	1.7
	Actual	15.6	.5	2.0	6.0	.4	0.6	3.3	1.1	1.7
UH-1	Main									
	Inherent	10.8	1.0	-	-	.5	2.4	3.5	0.8	2.6
	Actual	31.4	1.0	2.4	8.1	4.0	2.4	8.9	0.8	2.6
AH-1	Main									
	Inherent	10.0	0.6	-	-	.5	2.0	3.5	0.8	2.6
	Actual	27.2	0.6	1.9	6.4	4.0	2.0	8.9	0.8	2.6
CH-47	Combining									
	Inherent	6.6	1.1	-	-	1.2	-	3.8	0.5	-
	Actual	7.6	1.0	-	-	1.2	-	3.8	0.5	.4
CH-47	Aft									
	Inherent	31.0	0.8	-	-	2.0	0.5	26.7	0.5	0.5
	Actual	39.0	0.8	0.4	4.5	2.5	0.5	26.7	0.5	0.5
CH-47	Forward									
	Inherent	22.6	1.1	-	-	2.0	-	12.4	0.2	6.9
	Actual	39.0	1.0	1.5	10.6	6.7	-	12.4	0.2	6.9
CH-54	Main									
	Inherent	34.5	1.1	-	-	2.0	2.2	24.0	3.2	2.0
	Actual	97.7	1.1	-	45.2	20.0	2.2	24.0	3.2	2.0

[a]Build-up items are items which must be transferred between the transmission being removed and the one being installed off-aircraft and in the field.

mounting of other components on the transmission that appreciably affect on-aircraft repair. Configuration control authority has to be exercised from the very start of design to prevent drive train components from being masked by other components. Consideration, for example, should be given to innovative design concepts that allow main transmission removal without the need for disturbing the rotor head or flight controls.

USAAMRDL conducted several studies to identify the installation and repair characteristics of current Army helicopters that consume high maintenance manhours. Design improvements were studied and suggestions recommended for several of the more significant problems. Table C-3 summarizes these by component.

It is felt that the advent of on-condition maintenance will give rise to more part/module replacement than is currently performed. One way to reduce the expensive depot maintenance burden is to reduce the number of reasons for returning a gearbox to depot. All input and output seals should be field replaceable. More overrunning clutch failures should be experienced with TBO's being removed. Consequently, it is felt that the overrunning clutches should be modularized and made field replaceable.

FOUR-LEVEL VS THREE-LEVEL MAINTENANCE ORGANIZATION

The transition from a four-level maintenance organization to a three-level organization is not expected to produce any significant effect on transmission maintenance. Table C-4 compares the two maintenance organization concepts. It is important to realize that, except for depot maintenance, most repairs currently involve only very limited disassembly, primarily the replacement of parts such as drive shaft seals, oil filters, and sight glasses. This policy should not change with a three-level system. With such a policy, designs that employ modular replacement rather than an entire gearbox must be emphasized.

CORRECTIVE MAINTENANCE ESTIMATION

Three methods were explored for designing to maintainability requirements of helicopter drive systems. The three methods considered (time line analysis, historical task element analysis, and qualitative maintainability analysis) have their advantages and limitations. A discussion of each is provided in the remaining sections of this appendix.

Time Line Analysis

Time line analysis* is a standard technique for estimating the number of manhours associated with any repair. The analysis begins by defining the specific repair**; for example, on-aircraft intermediate gearbox removal and replacement. Next, the step-by-step task description is outlined and

---

*This technique is also known as maintenance task analysis.

**The term repair is synonomous with any corrective maintenance action including component removal/replacement.

an estimate made of the number of men and the elapsed time required for each step. Any special tools needed are also noted. The number of men are estimated on the basis of the size, and weight of the item, the manner in which the item is handled, and complexity of the task. The estimated time is based on the judgment of the estimator.

In estimating the maintenance manhours per flight hour, many types of repairs have to be estimated for each component. The number of possible repairs, especially at depot, could be large. While on-aircraft maintenance could be limited to part/component removal and replacement, depot maintenance has to consider many other facets besides primary failures. Secondary damage and the condition of parts that have not failed have to be considered.

For components such as the main transmission, this would greatly expand the number of possible repairs. Even applying engineering judgment to limit the number of possible variations for each primary failure mode, the number of analyses would be large. At present, such an analysis could only be attempted by an engineer experienced with past overhauls and repairs of previous helicopter transmissions. As a result, the time line analysis approach could not be readily integrated into the design process except possibly for on-aircraft maintenance actions.

Historical Time Element Analysis

Historical time element analysis allows rapid estimation of maintenance manhours for any repair. This technique describes each repair in terms of discrete, standard task elements. Manhour estimates are determined from historical data applicable to a particular component and similar type of aircraft. Historical data must be adjusted to reflect differences between the new design and the one in the data bank. This adjustment would be based on judgment as to the relative improvement afforded by the new design in eliminating problems associated with the component in the data bank.

At present, there are only historical data for on-aircraft removal and for replacement of components listed in Table C-1. This limited data is usable to provide some general installation features that would improve maintainability characteristics.

At present, there is only data available for the CH-54 to extend the technique to depot maintenance. Even for the CH-54, considerable analysis would be needed before the available information would be usable. Secondary damage and the condition of parts that had not failed would have to be considered. This approach would have to be limited to determining the extent of disassembly and assembly to obtain reasonable results, as shown by Table C-5. This table shows the percentage that each task element contributes to the overhaul of each CH-54 gearbox.

Table C-5 shows that disassembly and assembly processes are the chief contributors to depot maintenance.

TABLE C-3. DESIGN IMPROVEMENTS

MAINTENANCE CHARACTERISTICS	DESIGN IMPROVEMENT/COMMENT
<u>Input/Output Seals</u> Access to transmission seals in some installations is confining and creates an uncomfortable working position for the mechanic.	Maintenance tasks that are hard to perform are prone to error. Configuration control has to be exercised to prevent drive train components from being masked by other components.
In some installations, seal replacement requires removal of the gearbox or quill assembly.	Seal design should permit seal replacement on the aircraft without gearbox removal.
In some installations, an interference fit for the quill assembly or seal housing requires the housing bore or seal housing be heated to allow for expansion during seal insertion.	None
In some installations, a special puller is used for seal replacement. Occasionally fingers distort or a metal screw pulls out of the metal shell of the lip seal.	The design of special tools should be verified for mechanical integrity during development.
In some installations, a spanner-type retaining nut must be torqued and safetied with a locking ring during reinstallation of the seal housing. The nut has radially drilled holes which must align with the axial slot in the outside diameter of the input shaft that accepts the locking ring. A mechanic must probe for the slot with a piece of lockwire to find which hole aligns with the slot.	Locking systems that employ serrated locking rings would simplify safetying task.
Carbon face seals are particularly susceptible to damage of the primary sealing member due to nicks and scratches from handling and shipping. Additionally, some seals must be soaked for 24 hours prior to installation.	If new seals were packaged in an oil-filled, leak-proof container that provided a ready-to-install seal, soaking requirements could be eliminated and damage from handling and shipping minimized.

TABLE C-3. DESIGN IMPROVEMENTS (Continued)

MAINTENANCE CHARACTERISTICS	DESIGN IMPROVEMENT/COMMENT
Main Transmission Replacement of main transmission requires removal and re-installation of other components. These are rotor, flight control, hydraulic, and transmission accessories.	Some transmission accessories can be made integral assemblies of the transmission. Consideration should also be given to design concepts that allow the main transmission to be removed without disturbing the rotors or flight controls.
Soft-mounted transmissions have incurred an excessive expenditure of maintenance resources during replacement. This maintenance is involved with inspecting the details of the soft-mount assembly as well as performing any corrective maintenance that might be needed.	Hard-mounting the transmission reduces the time involved in the replacement process. Alignment of the main and tail drive is more constant. If soft mounting is desired, these considerations must be addressed.
Installations that employ barrel nuts at the transmission mount points require time aligning the bolt with the captured nut. Some difficulty is experienced and occasionally cross threading occurs.	Consideration must be given to those replacements that are attempted with poor lighting and possible under adverse weather conditions. Positioning the gearbox with a maintenance crane also adds to the difficulty. Piloted bolts would simplify engagement and reduce the possibility of cross threading. Such bolts are heavier and more costly.
The requirement for using hydraulic torque wrenches requires set-up and clean-up time. Previous wrenches were heavy and difficult to work with on the aircraft.	Mechanical torque wrenches should be used when possible.

TABLE C-3. DESIGN IMPROVEMENTS (Continued)

MAINTENANCE CHARACTERISTICS	DESIGN IMPROVEMENT/COMMENT
Checking and re-torquing mounting bolts incurs additional preventive maintenance.	Mounting bolts with large surface area washers maximize seating, and distribute the bolt load over a large bearing area to minimize pinch loss due to reseating and fretting. Surface coatings may be employed to reduce the coefficient of friction and the amount of fretting. Apart from positive locking, which adds weight and cost, retorquing can only be minimized.
Plumbing connections, such as elbows, unions, and reducers on some installations have to be transferred from the old to the new transmission whenever there is a *replacement*.	Plumbing connections can be made part of the transmission assembly, thereby eliminating the need for any transfer and the opportunity for stripped threads in the casting, which are costly to repair.
In some installations, the newly installed transmissions must be leveled, after which alignment of the main drive shaft must be checked and adjusted. Alignment procedures are complex and time consuming and offer the opportunity for occasional maintenance error.	The need for alignment should be minimized. Poor lighting and possible adverse weather conditions make the elimination of alignment desirable.
In some installations, whenever the oil filter is inspected or cleaned, the oil level in the tank must be drained to a level below the filter, an oil hose detached, and retention nuts removed.	Filters with pop-out indicators should be used for ease of maintenance. Filter design should incorporate features that would eliminate the need for oil draining.
Special tools that strip or yield after being used a couple of times unduly increase the time and difficulty of a repair.	Design of special tools should be verified for mechanical integrity during development.

TABLE C-3. DESIGN IMPROVEMENTS (Continued)

MAINTENANCE CHARACTERISTICS	DESIGN IMPROVEMENT/COMMENT
In some installations, every time the transmission is replaced the drive flanges must be indexed on assembly and drilled to receive a retaining bolt. This process is time consuming and must be performed by a relatively highly skilled mechanic.	The need for special tools and skilled mechanics in replacing a dynamic component should be eliminated.
In some installations, the transmission must be mated with the rotor shaft as part of the field replacement. This requires that a great deal of care be exercised to prevent damage to the transmission output seal. As a precaution, the seal and seal retainer are removed from the assembly, carefully worked onto the lower end of the rotor shaft, and finally reattached to the transmission housing as the transmission is raised higher.	A rotor shaft integral with the gearbox eliminates this task as a field repair. Gearbox removal and replacement should not subject a shaft seal to potential bumping, nicking, or the possibility of being distorted when installed on the shaft.
Intermediate/Tail Rotor Gearbox Replacement of the tail rotor gearbox requires removal and reinstallation of the tail rotor.	Consideration should be given to design concepts that allow gearbox removal without disturbance of the tail rotor. TR75-7 discusses several concepts. Life-cycle cost must be a prime consideration.
Drive Shaft Support Bearings In some installations, support bearings must be transferred from the old to the new drive shaft whenever a shaft is replaced. The number of support bearings transferred depends on the particular installation. In some instances where they are mounted in series, numerous bearings must be transferred.	Consideration should be given to design concepts that allow drive shaft removal without need for transferring support bearings. Several concepts are explored in TR75-7.
In some installations, the gap between the shaft and attachment flanges must be measured and shimmed prior to installing the shaft.	Consideration should be given to design concepts that minimize if not eliminate the need for shimming. Several concepts are explored in TR75-7.

TABLE C-3. DESIGN IMPROVEMENTS(Continued)

MAINTENANCE CHARACTERISTICS	DESIGN IMPROVEMENT/COMMENT
Bolt circles used to connect drive shaft to other components consume a major portion of the maintenance time needed whenever drive shafts are removed or disconnected.	Consideration should be given to a quick-disconnect scheme. The scheme should be simple and foolproof to prevent improper assembly. Shaft balance and weight impose constraints on the concept.
<u>Thomas Couplings</u> Changing the sequence of discs within the stack-up, or changing the orientation of any single disc, renders the coupling unusable.	A simple indexing system, with permanently applied marks, would allow restacking of discs in their original order after accidental disarrangement.

TABLE C-4. MAINTENANCE LEVEL COMPARISON

Category	Aviation Unit Maintenance	Aviation Intermediate Maintenance	Depot Maintenance
4-Level	Organizational Maintenance	Direct Support Maintenance; General Support Maintenance	Depot Maintenance
3-Level	Wherever Aircraft Are Located	In Mobile and/or Semi-Fixed Shops	In Base Depot or Aircraft Manufacturer's Facility
Basis	Repair and Keep It	Repair and Return to User	Repair for Stock
Type of Work Done	Inspection Servicing Adjustment Minor Repairs and Modifications	Inspection Complicated Adjustment Major Repairs and Modfications Major Replacement Overload from Lower Echelons	Inspection Most Complicated Adjustments Repairs and Replacement Including Complete overhaul and Rebuild Overload from Lower Echelons

TABLE C-5. TASK ELEMENT CONTRIBUTION TO CH-54 GEARBOX OVERHAULS

Task Element	Main Gearbox (Percent)	Intermediate Gearbox (Percent)	Tail Rotor Gearbox (Percent)
Disassembly	17.8	11.9	10.3
Magnaflux/Zyglo Inspection	6.4	6.5	6.3
Evaluation	6.4	4.3	7.1
Rework	8.9	7.3	5.6
Machine Shop	3.2	16.3	7.9
Shot Peen	0.4	5.2	2.4
Assembly	33.9	23.9	30.1
Test	3.9	8.7	12.7
Shipping Preparation	4.0	2.6	2.4
Bonding	3.5	-	-
Paint and Caulking	3.9	4.8	5.6
Final Assembly Inspection	3.5	3.9	4.8
Packaging	4.2	4.3	4.8

Qualitative Maintainability Analysis

A qualitative approach allows the factors that influence maintainability characteristics to be considered during design. These factors primarily include the maintenance characteristics cited in Table C-3 and those associated with disassembly and reassembly of depot-repairable components. This approach, unlike others previously considered, is applicable to all levels of maintenance and is feasible now.

For this approach to work, several related activities must take place. The designer must be informed of any significant departure from past experience to allow proper consideration during preliminary design. If an on-aircraft maintenance improvement were contemplated, configuration would have to be controlled from thepreliminary design phase. R&M personnel have to review with design engineers the maintainability aspects of the design as it progresses. Problems are addressed and corrective action taken, as appropriate, as early as possible in the design process.